

BLE Antenna Testing  
Helps Optimize IoT  
Device Performance **p35**

Transceiver IC  
Eases Transition from  
4G to 5G **p70**

Pointing to Progress in  
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Stations **p78**

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## READY FOR TAKEOFF

3D printing can  
build RF/microwave  
components for  
demanding space  
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### Model: LM-10M2D5G-100CW-1KWP-SFF

<http://www.pmi-rf.com/Products/limiters/LM-10M2D5G-100CW-1KWP-SFF.htm>

|                       |  |
|-----------------------|--|
| Frequency             | 0.01 to 2.5 GHz  |
| Insertion Loss        | 0.5 dB Typ - <b>Measured 1.09 dB</b>   |
| VSWR                  | 1.3:1 Max (@ -10 dBm input)<br><b>Measured Input: 1.28:1, Output: 1.22:1</b> |
| Input Power           | 100 watts CW Max, 1 kW peak<br>(1% duty cycle, 1 $\mu$ s Max pulse width)    |
| Recovery Time         | 1 $\mu$ s Max - <b>Measured 100 ns</b>                                       |
| Maximum Flat Leakage  | 13 dBm Max   |
| Operating Temperature | -55 °C to +85 °C   |



Package Size: **1.86" x 0.65" x 0.38"**  
Connectors: **SMA Female**

### Model: LM-1G2G-4CW-1KWP-SMF

<http://www.pmi-rf.com/Products/limiters/LM-1G2G-4CW-1KWP-SMF.htm>

|                       |   |
|-----------------------|---|
| Frequency             | 1.0 to 2.0 GHz  |
| Insertion Loss        | 0.7 dB Max - <b>Measured 0.65 dB</b>                                    |
| VSWR                  | 2.0:1 Max (@ -10 dBm input)<br><b>Measured 1.54:1</b>                   |
| Input Power           | 4 Watts CW Max, 1 kW peak<br>(1% duty cycle, 1 $\mu$ s Max pulse width) |
| Recovery Time         | 1 $\mu$ s Max - <b>Measured 100 ns</b>                                  |
| Maximum Flat Leakage  | 16 dBm Max (40 mW) - <b>Measured 15.35 dBm</b>                          |
| Operating Temperature | -55 °C to +85 °C  |



Package Size: **1.0" x 0.75" x 0.38"**  
Connectors: **SMA Female**

### Model: LM-6D7G7D9G-30W-SFF

<http://www.pmi-rf.com/Products/limiters/LM-6D7G7D9G-30W-SFF.htm>

|                       |  |
|-----------------------|--|
| Frequency             | 6.7 to 7.9 GHz   |
| Insertion Loss        | 1.1 dB Max - <b>Measured 0.96 dB</b>                             |
| VSWR                  | 1.5:1 Max (@ -20 dBm input)<br><b>Measured 1.38:1</b>            |
| Input Power           | 30 Watts CW Max  |
| Recovery Time         | 10 $\mu$ s Max - <b>Measured 70 ns</b>                           |
| Maximum Flat Leakage  | 18 dBm Max at Input Power of 30 W CW<br><b>Measured 7.05 dBm</b> |
| Operating Temperature | -40 °C to +85 °C   |



Package Size: **1.0" x 0.65" x 0.38"**  
Connectors: **SMA Female**

### Model: LM-6G18G-15-10W-SFF

<http://www.pmi-rf.com/Products/limiters/LM-6G18G-15-10W-SFF.htm>

|                       |  |
|-----------------------|--|
| Frequency             | 6.0 to 18.0 GHz                              |
| Insertion Loss        | 2.5 dB Typ @ 0 dBm - <b>Measured 1.71 dB</b> |
| VSWR                  | 1.8:1 Typ - <b>Measured 1.69:1</b>           |
| Input Power           | 10 Watts CW Max                              |
| Recovery Time         | <b>Measured 12.2 ns</b>                      |
| Maximum Flat Leakage  | +15 dBm Typ                                  |
| Operating Temperature | -55 °C to +85 °C                             |



Package Size: **1.0" X 1.0" X 0.5"**  
Connectors: **SMA Female**

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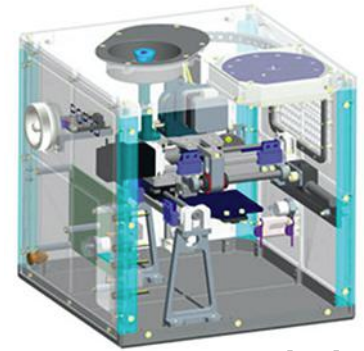
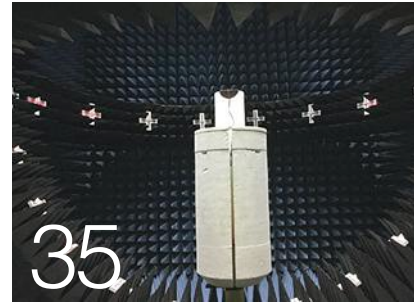
Learn more at [awrcorp.com/5g](http://awrcorp.com/5g)



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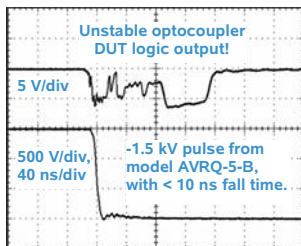


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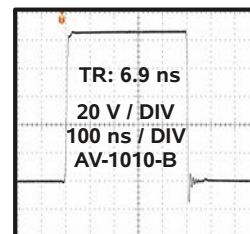


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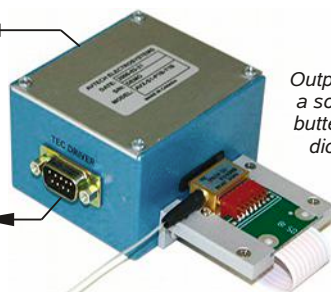


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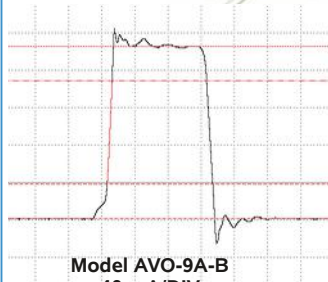
## Nanosecond Laser Diode Drivers With Butterfly Diode Sockets

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To TEC Controller



Output module with a socket-mounted butterfly-packaged diode installed.



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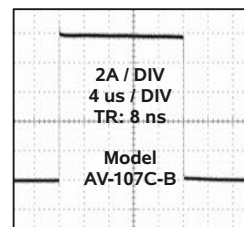


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|--------|--------------------|---------------|--------------|
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| AV-106 | 5 - 100 A, 100 V   | 0.5 us - 1 ms | 50 ns - 1 us |
| AV-108 | 12.5 - 200 A, 100V | 2 us - 1 ms   | 5 - 15 us    |
| AV-109 | 10 - 100 A, 5 V    | 10 us - 1 s   | 10 us        |
| AV-156 | 2 - 30 A, 30 V     | 1 us - 100 ms | 0.2 - 50 us  |

Avtech has a long history of producing one-of-a-kind custom units.



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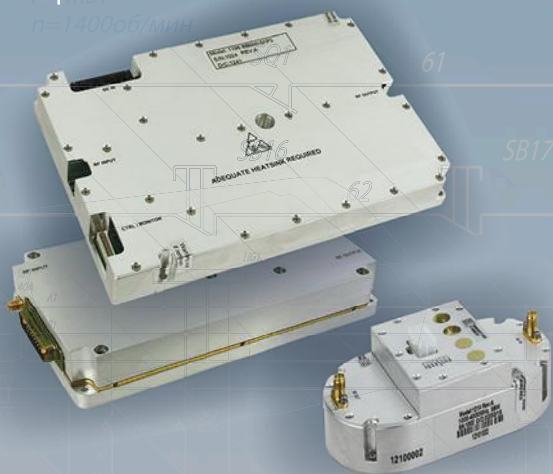
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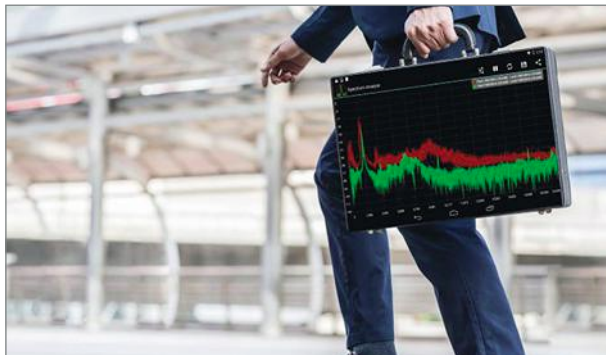


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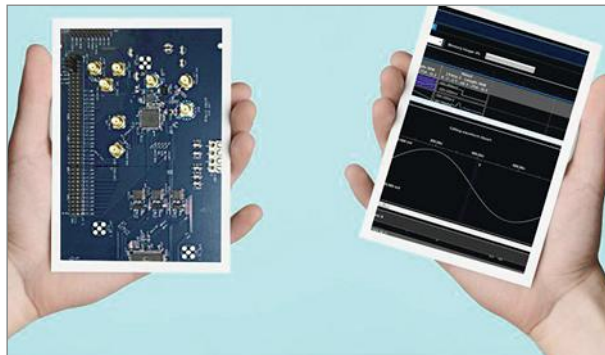
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## Carry Spectrum Analysis With You

A rapidly growing trend within the RF/microwave industry is the portability of test equipment. Such is the case with the spectrum analyzer, which now can be found in various handheld sizes. Today, several different test-and-measurement suppliers offer USB-based spectrum analyzers. Let's take a look at one product that exemplifies this trend.

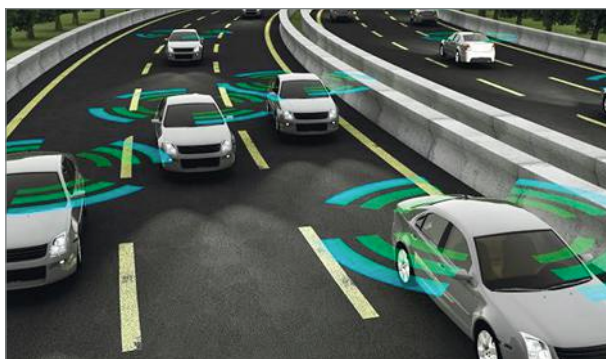
<http://www.mwrf.com/test-measurement/carry-spectrum-analysis-you>



## AWG vs. DDS: Sources of Contention

High-frequency signal sources based on digital techniques include arbitrary waveform generators (AWGs) and direct digital synthesizers (DDSs). Both types of signal sources have gained in frequency and bandwidth over the years, thanks to the enhanced performance of digital components such as digital-to-analog converters (DACs).

<http://www.mwrf.com/test-measurement/awg-vs-dds-sources-contention>



## The Battle Over V2V Wireless Technologies

The National Highway Traffic Safety Administration (NHTSA) thought the final decision had been made: The Dedicated Short Range Communications (DSRC) standard would be the official wireless technology for use in vehicle-to-vehicle (V2V) communications, as defined by the Intelligent Transportation Systems (ITS) program. Now, however, that decision seems to be up in the air.

<http://www.mwrf.com/systems/battle-over-v2v-wireless-technologies>



## Managing the Coexistence of Multiple Wireless Systems

While it would be ideal to have different frequencies for each wireless standard, as with radio and television broadcast channels, frequency spectrum is limited. The growing number of wireless standards makes it difficult, if not impossible, to allocate separate frequency spectrum for each standard.

<http://www.mwrf.com/systems/managing-coexistence-multiple-wireless-systems>



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\*See datasheet for suggested application circuit for PMA3-83LN+

†Flatness specified over 0.5 to 7 GHz

### FEATURES:

- Low Noise Figure, 1.3 dB
- High Gain, 21 dB
- Excellent Gain Flatness,  $\pm 0.7$  dB<sup>†</sup>
- High IP3, +35 dBm
- High POUT, +23.2 dBm



## Editorial

JACK BROWNE

Technical Contributor

jack.browne@penton.com

# Once Again, IMS Was Worth the Trip



In an age of virtual events and almost an entire day spent on a cellular telephone or an Internet connection of some kind, an event such as the recent 2017 IMS in Hawaii has enormous value to the community that is the RF/microwave industry—and this is very much a community where everyone knows one another and little goes on in secret. It is a chance to remember the human side of the RF/microwave industry and, for many, a chance to remember why they chose to be a part of the industry.

Each IMS provides the structure for smaller gatherings, in technical conferences, at workshops, at exhibition booths, even at company-sponsored MicroApps sessions. These latter sessions (held in an exhibition booth on the show floor) have gained in popularity as kind of casual, semi-technical sessions with practical application advice on particular products. Each IMS over the years has been unique and most visitors can recall something or someone from each of the shows they have attended. They may also remember where they were in their careers for each show, and how each show served as a kind of yardstick for measuring their personal growth. In fact, more than a few industry members are already looking forward to the 2018 IMS in Philadelphia.

It is the personal interactions, whether in technical sessions or on the show floor, that are so valuable at IMS. In many ways, the event serves as a reminder of the uniqueness of the RF/microwave portion of the electronics industry. It is a relatively small portion of the total electronics industry, long based on performing specialized design tasks related to military electronic systems. While defense-related requirements are still an important part of the industry, the increasing importance of wireless communications has changed the industry, made it more commercial, and made many of its members deal with what has been called the “commercialization” or “commoditization” of the industry.

The real-time, personal interactions at IMS are far more meaningful than quick texts and stacks of e-mails. This is especially true for an industry that is also facing a transition in terms of the increasing average age of its engineers. Personal interactions provide opportunities for younger engineers to learn about other companies and other technologies, and perhaps pave the way for their own futures even as they ensure the future of another company and of the industry.

IMS may not always be in everyone's most convenient location, but it is always a meaningful event and well worth the trip. It is a chance to learn, to remember, and to interact with fellow members of a unique industry for a few days without some of the electronic devices that, ironically, this industry has made possible. **mw**

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## HIGH POWER BROAD BAND

### LIMITERS

0.5 - 12 GHz

New

25 WATT CW



- Low Limiting Threshold (+6 dBm Typical)
- 25 Watt CW and 200 Watt Peak (1 microsec) power handling capability
- Built-in DC Block @ input and output
- Hermetically Sealed Module
- Typical Recovery Time is less than 10 Microsec

#### Typical Performance @ +25 Deg. C

| MODEL       | FREQ. RANGE (GHz) | MAX. INSERT. LOSS (dB) | MAX VSWR | MAX LEAKAGE @ 25 W CW INPUT (dBm) |
|-------------|-------------------|------------------------|----------|-----------------------------------|
| LS0510P25A  | 0.5 - 1.0         | 0.5                    | 1.4:1    | +20                               |
| LS0520P25A  | 0.5 - 2.0         | 0.6                    | 1.4:1    | +20                               |
| LS0540P25A  | 0.5 - 4.0         | 0.7                    | 1.4:1    | +20                               |
| LS0560P25A  | 0.5 - 6.0         | 1.3                    | 1.5:1    | +20                               |
| LS05012P25A | 0.5 - 12.0        | 1.7                    | 1.6:1    | +20                               |
| LS1020P25A  | 1.0 - 2.0         | 0.6                    | 1.4:1    | +20                               |
| LS1060P25A  | 1.0 - 6.0         | 1.2                    | 1.5:1    | +20                               |
| LS1012P25A  | 1.0 - 12.0        | 1.6                    | 1.6:1    | +20                               |
| LS2040P25A  | 2.0 - 4.0         | 0.7                    | 1.4:1    | +20                               |
| LS2060P25A  | 2.0 - 6.0         | 1.2                    | 1.5:1    | +20                               |
| LS2080P25A  | 2.0 - 8.0         | 1.3                    | 1.6:1    | +20                               |
| LS4080P25A  | 4.0 - 8.0         | 1.3                    | 1.5:1    | +18                               |
| LS7012P25A  | 7.0 - 12.0        | 1.6                    | 1.6:1    | +18                               |

**Note: 1. Insertion Loss and VSWR tested at -10 dBm.**

**Note: 2. Typical limiting threshold: +6 dBm.**

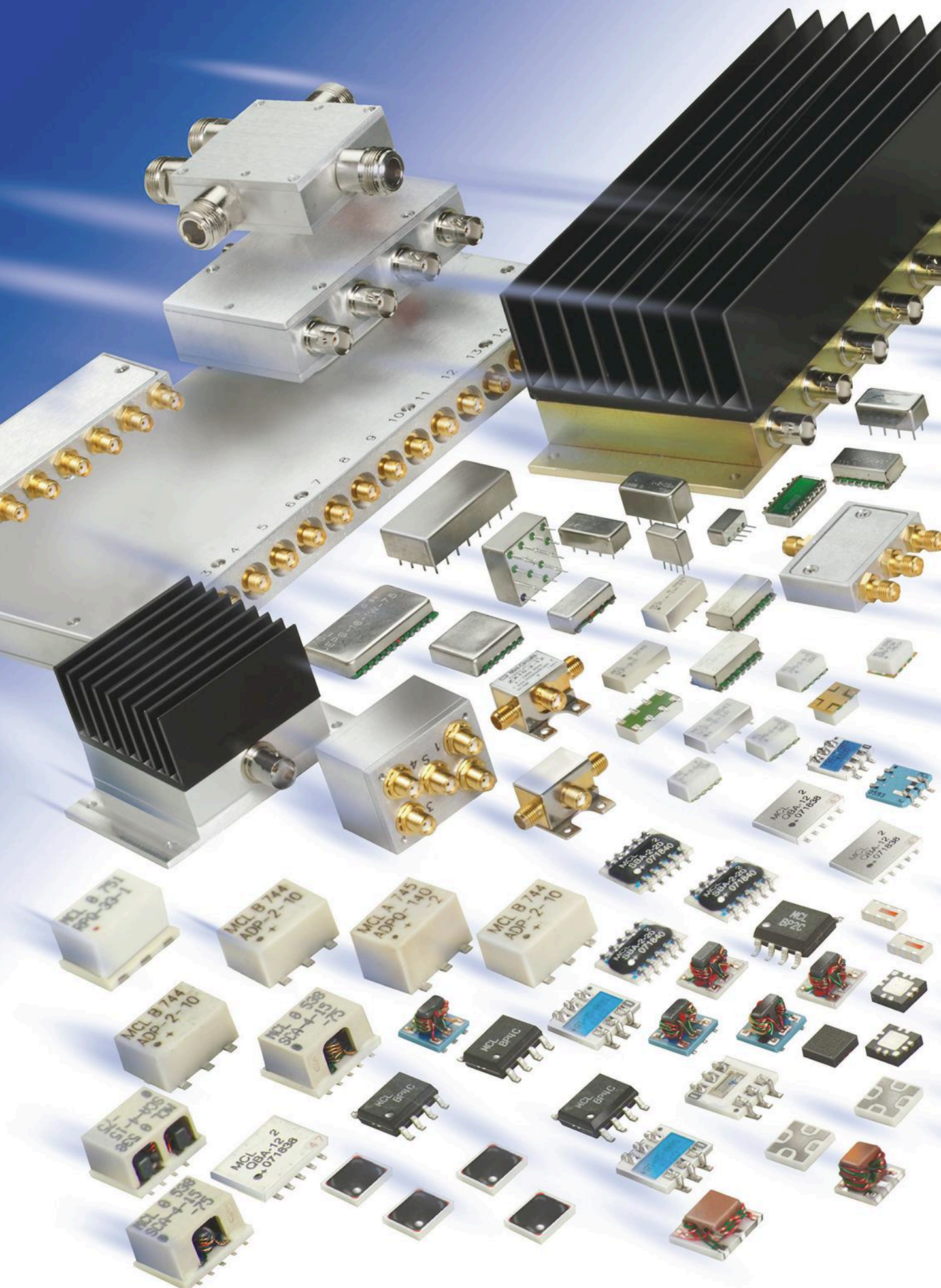
**Note: 3. Power rating derated to 20% @ +125 Deg. C.**

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## OCTAVE BAND LOW NOISE AMPLIFIERS

| Model No.   | Freq (GHz) | Gain (dB) MIN | Noise Figure (dB) | Power-out @ P1-dB | 3rd Order ICP | VSWR  |
|-------------|------------|---------------|-------------------|-------------------|---------------|-------|
| CA01-2110   | 0.5-1.0    | 28            | 1.0 MAX, 0.7 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA12-2110   | 1.0-2.0    | 30            | 1.0 MAX, 0.7 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA24-2111   | 2.0-4.0    | 29            | 1.1 MAX, 0.95 TYP | +10 MIN           | +20 dBm       | 2.0:1 |
| CA48-2111   | 4.0-8.0    | 29            | 1.3 MAX, 1.0 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA812-3111  | 8.0-12.0   | 27            | 1.6 MAX, 1.4 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA1218-4111 | 12.0-18.0  | 25            | 1.9 MAX, 1.7 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA1826-2110 | 18.0-26.5  | 32            | 3.0 MAX, 2.5 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |

## NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

| Model No.   | Freq (GHz)   | Gain (dB) MIN | Noise Figure (dB) | Power-out @ P1-dB | 3rd Order ICP | VSWR  |
|-------------|--------------|---------------|-------------------|-------------------|---------------|-------|
| CA01-2111   | 0.4 - 0.5    | 28            | 0.6 MAX, 0.4 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA01-2113   | 0.8 - 1.0    | 28            | 0.6 MAX, 0.4 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA12-3117   | 1.2 - 1.6    | 25            | 0.6 MAX, 0.4 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA23-3111   | 2.2 - 2.4    | 30            | 0.6 MAX, 0.45 TYP | +10 MIN           | +20 dBm       | 2.0:1 |
| CA23-3116   | 2.7 - 2.9    | 29            | 0.7 MAX, 0.5 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA34-2110   | 3.7 - 4.2    | 28            | 1.0 MAX, 0.5 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA56-3110   | 5.4 - 5.9    | 40            | 1.0 MAX, 0.5 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA78-4110   | 7.25 - 7.75  | 32            | 1.2 MAX, 1.0 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA910-3110  | 9.0 - 10.6   | 25            | 1.4 MAX, 1.2 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA1315-3110 | 13.75 - 15.4 | 25            | 1.6 MAX, 1.4 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA12-3114   | 1.35 - 1.85  | 30            | 4.0 MAX, 3.0 TYP  | +33 MIN           | +41 dBm       | 2.0:1 |
| CA34-6116   | 3.1 - 3.5    | 40            | 4.5 MAX, 3.5 TYP  | +35 MIN           | +43 dBm       | 2.0:1 |
| CA56-5114   | 5.9 - 6.4    | 30            | 5.0 MAX, 4.0 TYP  | +30 MIN           | +40 dBm       | 2.0:1 |
| CA812-6115  | 8.0 - 12.0   | 30            | 4.5 MAX, 3.5 TYP  | +30 MIN           | +40 dBm       | 2.0:1 |
| CA812-6116  | 8.0 - 12.0   | 30            | 5.0 MAX, 4.0 TYP  | +33 MIN           | +41 dBm       | 2.0:1 |
| CA1213-7110 | 12.2 - 13.25 | 28            | 6.0 MAX, 5.5 TYP  | +33 MIN           | +42 dBm       | 2.0:1 |
| CA1415-7110 | 14.0 - 15.0  | 30            | 5.0 MAX, 4.0 TYP  | +30 MIN           | +40 dBm       | 2.0:1 |
| CA1722-4110 | 17.0 - 22.0  | 25            | 3.5 MAX, 2.8 TYP  | +21 MIN           | +31 dBm       | 2.0:1 |

## ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

| Model No.   | Freq (GHz) | Gain (dB) MIN | Noise Figure (dB) | Power-out @ P1-dB | 3rd Order ICP | VSWR  |
|-------------|------------|---------------|-------------------|-------------------|---------------|-------|
| CA0102-3111 | 0.1-2.0    | 28            | 1.6 Max, 1.2 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA0106-3111 | 0.1-6.0    | 28            | 1.9 Max, 1.5 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA0108-3110 | 0.1-8.0    | 26            | 2.2 Max, 1.8 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA0108-4112 | 0.1-8.0    | 32            | 3.0 MAX, 1.8 TYP  | +22 MIN           | +32 dBm       | 2.0:1 |
| CA02-3112   | 0.5-2.0    | 36            | 4.5 MAX, 2.5 TYP  | +30 MIN           | +40 dBm       | 2.0:1 |
| CA26-3110   | 2.0-6.0    | 26            | 2.0 MAX, 1.5 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA26-4114   | 2.0-6.0    | 22            | 5.0 MAX, 3.5 TYP  | +30 MIN           | +40 dBm       | 2.0:1 |
| CA618-4112  | 6.0-18.0   | 25            | 5.0 MAX, 3.5 TYP  | +23 MIN           | +33 dBm       | 2.0:1 |
| CA618-6114  | 6.0-18.0   | 35            | 5.0 MAX, 3.5 TYP  | +30 MIN           | +40 dBm       | 2.0:1 |
| CA218-4116  | 2.0-18.0   | 30            | 3.5 MAX, 2.8 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA218-4110  | 2.0-18.0   | 30            | 5.0 MAX, 3.5 TYP  | +20 MIN           | +30 dBm       | 2.0:1 |
| CA218-4112  | 2.0-18.0   | 29            | 5.0 MAX, 3.5 TYP  | +24 MIN           | +34 dBm       | 2.0:1 |

## LIMITING AMPLIFIERS

| Model No.   | Freq (GHz) | Input Dynamic Range | Output Power Range Psat | Power Flatness dB | VSWR  |
|-------------|------------|---------------------|-------------------------|-------------------|-------|
| CLA24-4001  | 2.0 - 4.0  | -28 to +10 dBm      | +7 to +11 dBm           | +/- 1.5 MAX       | 2.0:1 |
| CLA26-8001  | 2.0 - 6.0  | -50 to +20 dBm      | +14 to +18 dBm          | +/- 1.5 MAX       | 2.0:1 |
| CLA712-5001 | 7.0 - 12.4 | -21 to +10 dBm      | +14 to +19 dBm          | +/- 1.5 MAX       | 2.0:1 |
| CLA618-1201 | 6.0 - 18.0 | -50 to +20 dBm      | +14 to +19 dBm          | +/- 1.5 MAX       | 2.0:1 |

## AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

| Model No.    | Freq (GHz)  | Gain (dB) MIN | Noise Figure (dB) | Power-out @ P1-dB | Gain Attenuation Range | VSWR   |
|--------------|-------------|---------------|-------------------|-------------------|------------------------|--------|
| CA001-2511A  | 0.025-0.150 | 21            | 5.0 MAX, 3.5 TYP  | +12 MIN           | 30 dB MIN              | 2.0:1  |
| CA05-3110A   | 0.5-5.5     | 23            | 2.5 MAX, 1.5 TYP  | +18 MIN           | 20 dB MIN              | 2.0:1  |
| CA56-3110A   | 5.85-6.425  | 28            | 2.5 MAX, 1.5 TYP  | +16 MIN           | 22 dB MIN              | 1.8:1  |
| CA612-4110A  | 6.0-12.0    | 24            | 2.5 MAX, 1.5 TYP  | +12 MIN           | 15 dB MIN              | 1.9:1  |
| CA1315-4110A | 13.75-15.4  | 25            | 2.2 MAX, 1.6 TYP  | +16 MIN           | 20 dB MIN              | 1.8:1  |
| CA1518-4110A | 15.0-18.0   | 30            | 3.0 MAX, 2.0 TYP  | +18 MIN           | 20 dB MIN              | 1.85:1 |

## LOW FREQUENCY AMPLIFIERS

| Model No.  | Freq (GHz) | Gain (dB) MIN | Noise Figure (dB) | Power-out @ P1-dB | 3rd Order ICP | VSWR  |
|------------|------------|---------------|-------------------|-------------------|---------------|-------|
| CA001-2110 | 0.01-0.10  | 18            | 4.0 MAX, 2.2 TYP  | +10 MIN           | +20 dBm       | 2.0:1 |
| CA001-2211 | 0.04-0.15  | 24            | 3.5 MAX, 2.2 TYP  | +13 MIN           | +23 dBm       | 2.0:1 |
| CA001-2215 | 0.04-0.15  | 23            | 4.0 MAX, 2.2 TYP  | +23 MIN           | +33 dBm       | 2.0:1 |
| CA001-3113 | 0.01-1.0   | 28            | 4.0 MAX, 2.8 TYP  | +17 MIN           | +27 dBm       | 2.0:1 |
| CA002-3114 | 0.01-2.0   | 27            | 4.0 MAX, 2.8 TYP  | +20 MIN           | +30 dBm       | 2.0:1 |
| CA003-3116 | 0.01-3.0   | 18            | 4.0 MAX, 2.8 TYP  | +25 MIN           | +35 dBm       | 2.0:1 |
| CA004-3112 | 0.01-4.0   | 32            | 4.0 MAX, 2.8 TYP  | +15 MIN           | +25 dBm       | 2.0:1 |

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# Communications Receivers—Principles and Design

COMMUNICATIONS TECHNOLOGY HAS has gone through dramatic change over the past 40 years, as has most of electronics technology. Vacuum tubes were eventually replaced by solid-state transistors, and those discrete semiconductors have largely been

replaced by integrated circuits, as an increasing number of electronic functions continue to be compressed into smaller circuit and package sizes.

Dr. Ulrich Rohde—chairman of Synergy Microwave Corp.—has teamed with fellow authors Jerry Whitaker and Hans Zahnd to address a plethora of design issues related to modern communications receiver technologies. The 4th edition of their text *Communications Receivers—Principles and Design* (McGraw-Hill Education) is now available.

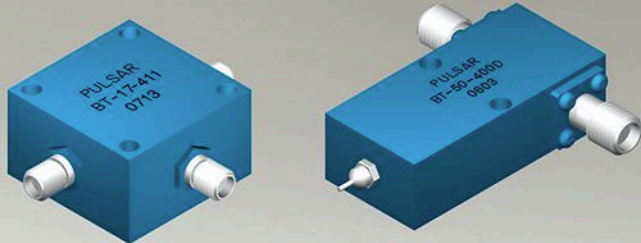
The book's 11 chapters explore both analog and digital receivers and their components, with special attention paid to the programmable software-defined radios (SDRs) that have become a popular architecture for commercial and military communications applications. The book includes in-depth studies of many of the components that are essential to communications receiver operation, including antennas and frequency mixers.

A number of design examples use block diagrams for two-way radios. One of the more practical block diagrams, in chapter 3, of a high-frequency (HF) receiver, is accompanied by a partial level diagram. The diagram shows noise figures, gains, and intercept points for each stage of the receiver front end for different operating conditions.

While *Communications Receivers* pays proper respect to analog receiver designs, it is an ambitious effort to cover digital receivers such as SDRs and the components that are so essential to them. Ultimately, this is a comprehensive single source that contains an enormous amount of information on communications receivers, and is a text that every system-level engineer will want in their collection. **mw**

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| Freq. Range        | Isolation (dB) min. | Insertion Loss (dB) max. | Current (mA) max. | VSWR max. | Model Number |
|--------------------|---------------------|--------------------------|-------------------|-----------|--------------|
| 50-800 MHz         | 25                  | 0.6                      | 6000              | 1.20:1    | BT-10-E      |
| 10-1000 MHz        | 25                  | 0.5                      | 1000              | 1.20:1    | BT-20        |
| 800-1000 MHz       | 30                  | 0.5                      | 5000              | 1.50:1    | BT-21        |
| 1700-2000 MHz      | 30                  | 0.5                      | 5000              | 1.50:1    | BT-22        |
| 500-2500 MHz       | 25                  | 1.0                      | 200               | 1.20:1    | BT-02        |
| 10-3000 MHz        | 25                  | 1.8                      | 3000              | 1.50:1    | BT-06-411    |
| 500-3000 MHz       | 25                  | 1.0                      | 500               | 1.20:1    | BT-05        |
| 500-3000 MHz       | 30                  | 1.8                      | 2000              | 1.50:1    | BT-23        |
| 10-4200 MHz        | 25                  | 1.2                      | 200               | 1.20:1    | BT-03        |
| 1000-5000 MHz      | 35                  | 1.0                      | 1000              | 1.50:1    | BT-04        |
| 100-6000 MHz       | 30                  | 1.5                      | 500               | 1.50:1    | BT-07        |
| 0.5-10 GHz         | 30                  | 1.0                      | 200               | 1.50:1    | BT-26        |
| 100 KHz - 12.4 GHz | 40                  | 1.5                      | 700               | 1.60:1    | BT-52-400D   |
| 100 KHz - 18.0 GHz | 40                  | 2.0                      | 700               | 1.60:1    | BT-53-400D   |
| 0.3-18.0 GHz       | 25                  | 1.5                      | 500               | 1.60:1    | BT-29        |
| 30 KHz - 27.0 GHz  | 40                  | 2.2                      | 500               | 1.80:1    | BT-51        |
| 30 KHz - 40.0 GHz  | 40                  | 3.0                      | 500               | 1.80:1    | BT-50        |
| 30 KHz - 70.0 GHz  | 30                  | 3.5                      | 500               | 2.00:1    | BT-54-401    |
| 30 KHz - 85.0 GHz  | 30                  | 4.0                      | 500               | 2.00:1    | BT-55-401    |

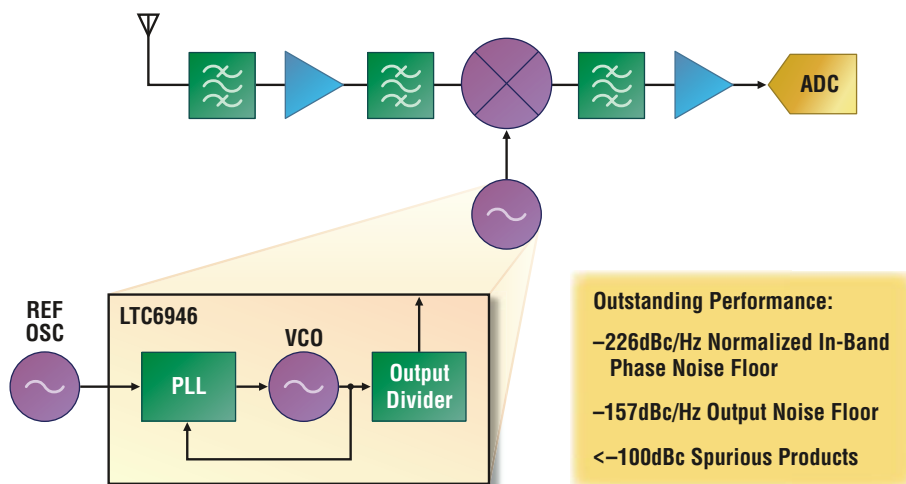
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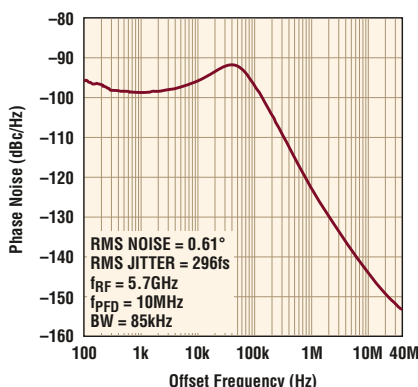
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# News

## What Frequency Bands Will Roll Out The Carpet for an OFFICIAL 5G STANDARD?

There has been lots of chatter about the wireless industry's shift to millimeter wave spectrum for 5G, but the official standard is likely to span lower bands currently used to the higher bands that companies are still learning how to make hardware for.

The 3GPP—the industry organization that stewards wireless standards—has scheduled next June as the point of no return for the specification. The 5G New Radio will not be changed any further after that and it is scheduled to be published as Release 15 in September 2018.

“Lots of LTE bands will be redeployed for new radio,” said Nikhail Kundargi, a senior wireless platform architect at National Instruments, in a presentation at the NI Week conference last month. “We have not finished distilling these frequencies into band combinations or band numbers yet, but we’re working on it.”

Kundargi presented a chart on what bands wireless carriers are newly targeting for standardization and not other efforts, specifications published by Verizon this year and South Korean companies that want to show off the technology for the Winter Olympics in Seoul next year.

But for now companies are making decisions about spectrum based on intermediary standards in between current LTE and the 5G standard. The current wireless technology for 4G, called LTE, will remain a dominant part of these early standards, acting like an anchor for a new 5G over-the-air technology.

Under pressure from companies like Verizon, the 3GPP has allowed for the publication of an official Non-standalone 5G specification, which would sate the appetites of wireless carriers for the better capabilities—and marketing might—of

| Frequency Range  | Supporting Companies (at least 3)  |
|------------------|--|
| 3.3 – 4.2 GHz    | NTT Docomo, KDDI, S8M, CMCC, China Unicom, China Telecom, KT, SK Telecom, LG Uplus, Etisalat, Orange |
| 4.4 – 4.99 GHz   | NTT Docomo, KDDI, S8M, CMCC, China Unicom, China Telecom,  |
| 24.25 – 29.5 GHz | NTT Docomo, CMCC, KT, Verizon, T-Mobile, Telecom Italia, BT  |
| 31.8 – 33.4 GHz  | Orange, Italia Telecom, British Telecom  |
| 37 – 40 GHz      | AT&T, Verizon, T-Mobile  |

5G before a full standard is finished. That specification has already been frozen and is scheduled to be completed by the end of the year, with non-standalone 5G ready for deployment by March next year, said Kundargi.

It is targeting fixed wireless to replace fiber. Kundargi said that one band to keep an eye on is the 3.5 GHz band, a frequency previously reserved for military applications that telecom regulators in the United States voted to open for a spectrum sharing experiment, in which it could be used like unlicensed spectrum by the public as long as the military was not using it. It is also ideal for small cells.

Other bands that companies are toying with the first phase of Release 15 include the 52 GHz and 70 GHz, which Nokia targeted as far back as 2012 with a prototyping system it built with National Instruments for 5G. AT&T has also been testing out the 28 GHz band, making a channel sounding machine that can roll through streets or buildings to see how the millimeter waves interacts with trees, walls, or people.

“The 3GPP will study how these bands work together because depending on how you put them together you might have harmonics,” said Kundargi. “Non-standalone 5G will pair an LTE and a new radio band. The anchor, [for instance], will be the 3 GHz band while your data connectivity resides in the 28 GHz band.” ■

## ECHODYNE RAISES \$29 MILLION for Seeing-Eye Radar

**ECHODYNE, A COMPANY** with ambitions to build radar imaging systems for drones and autonomous cars has raised \$29 million in its latest round of financing, another testament to the potential for metamaterials.

Echodyne's investors include Bill Gates, who has invested in several metamaterial ventures spun out of an investment and patent firm started by Nathan Myhrvold, a former Microsoft chief technology officer. Kymeta and Evolv Technology are two other firms that broke off Intellectual Ventures to sell metamaterial products.

The funding is the latest show of support for Echodyne, one of the few companies to take metamaterials out of the laboratory—to be used in automobiles and communications. These materials can bend light, sound, and radio waves in unnatural ways, using structures smaller than the wavelength of the energy being manipulated.

The company, based in Bellevue, Wash., is betting on a new type of electronically-steerable radar that takes cues from current military systems, like Raytheon's antiballistic missile radar. Instead of mechanically aiming radar beams in every direction, Echodyne's radar actively steer radio waves using electronics.

The systems work without the bulky and expensive phase shifters used in traditional electronically-scanning arrays. These components are replaced with repeating patterns of copper wire traced over ordinary circuit boards and stacked on top of each other, resulting in systems small and light enough to be equipped to drones.

Eben Frankenberg, Echodyne's chief executive, said in a statement that its systems have much higher resolution than normal radar, which can reliably identify the location of obstacles, but not the shape and size of surrounding objects. This "radar vision" involves pairing Echodyne's hardware with computer vision software to perceive, recognize, and classify everything from trees to cars to drones.

"Echodyne's radar vision platform is unique," said Greg Papadopoulos, a venture partner at New Enterprise Associates, which led the financing. He added that it "combines the fundamental all-



weather benefits of radar with the high-resolution imaging capabilities more often attributed to lidar or computer vision."

Those technologies are currently the sensors of choice for cars and drones, but their accuracy and range are limited in fog, rain, and snow. In contrast, Echodyne's radar works in poor weather conditions and also senses objects in the dark, making it a potentially valuable asset for autonomous cars and robots.

Echodyne's first commercial product—around the size of an Amazon Kindle—is designed to let drones perceive nearby aircraft, so that companies can fly out of the light of sight to survey farms or construction sites. The sensor can detect and track a helicopter up to 1.85 miles away and other large drones at a half mile.

Echodyne has raised \$44 million since its founding in 2014, a clear statement of the potential ascribed to metamaterials. Investors are pouring money into other metamaterial users: Kymeta, which sells satellite antennas for cars and other applications, has raised around \$217 million since 2012. Evolv has raised \$29 million for sensors to be used in airport security systems.

Echodyne plans to spend its fresh cash on making a short-range system for autonomous cars, as well as increasing production of its radar from hundreds of units per year to thousands, Frankenberg told technology news site TechCrunch. It has already sold out its first production run of drone radar systems. ■

## HOLOGRAMS STAND OUT In Sea of Wireless Signals

**AN EXPERIMENTAL SYSTEM** can take ghostly snapshots by measuring the reflections of the same Wi-Fi signals used for connecting to the internet. It has been suggested as a way of tracking packages in warehouses or mapping collapsed buildings to safely and quickly reach victims.

Writing in the journal *Physical Review Letters*, researchers at the Technical University of Munich reported a way to create a type of three-dimensional image or hologram using wireless signals. The holograms are somewhat similar to sound recordings, which store the vibrations of violins strings or vocal cords.

"Using this technology, we can generate a three-dimensional image of the space around the Wi-Fi transmitter, as if our eyes could see microwave radiation," said Friedmann Reinhard, a physicist who authored the report with his colleague Philip Holl, in a statement.

Their proof-of-concept experiment used an antenna sliding along a pole to measure from different angles Wi-Fi signals emanating from a router. Using specialized software to make sense of the measurements, the researchers created a holographic image of a cross, which they made out of aluminum foil.

The system is still in the early stages of development. But the researchers said later systems could have multiple antennas that take tons of snapshots, stitching them into a stop-motion animation of equipment moving around a factory or people walking through a home. It would result in “video-like image frequency,” Holl said.

Other researchers are also seeking ways to turn stray cellular and wireless signals into coarse images of people through buildings and walls. Dana Katabi, an electrical engineer at the Massachusetts Institute of Technology, and her colleagues have been tinkering with such technology for years.

In 2013, the researchers built a system that detects wireless reflections off the human body, spitting out a silhouette of a person standing behind a wall. Their device monitors how these wireless ripples change over time, using software to reconstruct the silhouette in shade of blue, yellow, and red.

“The data you get back from these reflections are very minimal,” said Katabi, whose research team has also devised wireless transmitters that clock walking speed, in a statement. “However, we can extract meaningful signals through a series of algorithms we developed that minimize the random noise produced by the reflections.” ■

## FOR PROTOTYPING, New Software-Defined Radio for Millimeter Waves

**NATIONAL INSTRUMENTS RELEASED** new radio heads that can be swapped into its millimeter wave transceiver system to measure how these high frequencies are affected by trees, buildings, cars, and people.

National Instruments’ radio heads operate over the 28 gigahertz frequency band, which exists much higher on the wireless spectrum than the scarce and expensive low frequency bands now used in communications. But wireless carriers like AT&T and Verizon are increasingly targeting the band and higher ones for 5G networks.

Starting in 2012, National Instruments partnered with Nokia to build 73 GHz radio heads for testing and prototyping. Tapping into the 28 GHz band takes little more than plugging in the new devices, since the software is compatible between the radio heads. (National Instruments also has 60 GHz heads for the transceiver).

“We knew we would need something modular where we could change the frequency bands,” said Sarah Yost, a product marketing manager at National Instruments, in an interview. “We gave it a flexible [intermediate frequency] so that we could tune into new radios in the future.”

The new radio heads follow a recent announcement that AT&T had used the prototyping system to build a tool for tapping into 28 GHz spectrum. The tool, called Porcupine for its crown of horn antennas, is helping the wireless carrier with tricky tasks like connecting vehicles and planning where to position 5G equipment for best coverage.

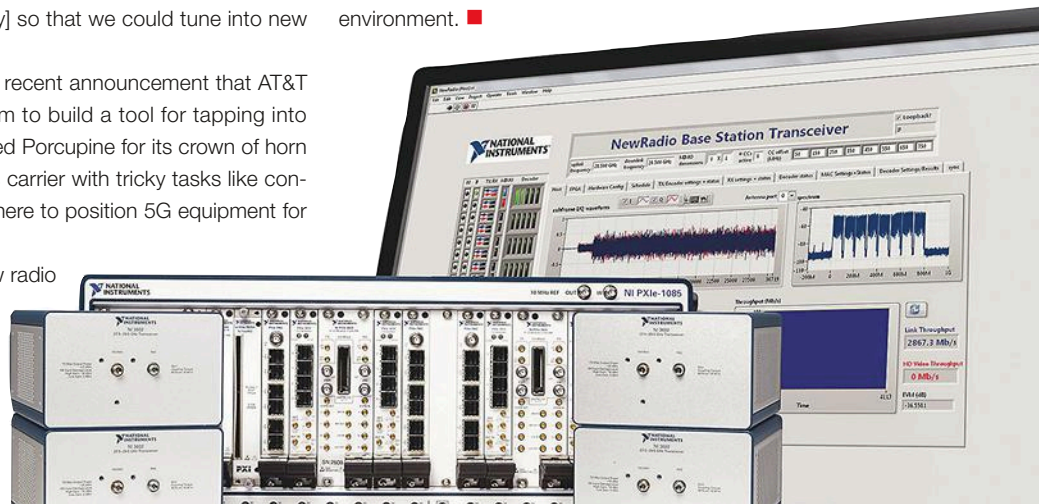
The decision to target the new radio heads at 28 GHz spectrum also came from projects around the wireless industry, Yost said. Recently, National Instruments showed the radio heads running a 5G specification that Verizon published separately this

year from the formal standards process. The company next plans to release 39 GHz radio heads.

These millimeter waves have hard-to-ignore qualities, including more breathing room for smartphone and other mobile communications. But millimeter waves cannot pass through buildings and walls and are absorbed more quickly by oxygen than lower bands. “On the trade-off, they provide significantly higher bandwidth,” Yost said.

In the view of telecom regulators and wireless carriers, the benefits are worth fighting for. Last year, officials in the United States voted to slice open new spectrum above 28 GHz. In recent months, wireless carriers have been bare-knuckle brawling for the rights to millimeter waves: Verizon recently won a \$3.1 billion bidding war for Straight Path, a major holder of 28 and 39 GHz licenses.

The software inside National Instruments’ platform also contains a physical communications layer that follows the rules of the proposed 5G standard. The physical layer is available as source code in LabView, National Instruments’ graphical programming environment. ■



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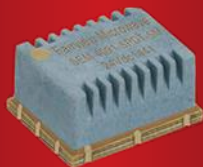
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## News

### CHIP MAKERS BUILD FORTUNES from RF MEMS

**IN 1959, THE** physicist Richard Feynman delivered the famous line that there would be “plenty of room at the bottom” with entire industries using microscopic machines to assemble computers or medicine atom-by-atom.

Over the next six decades, electrical engineers found plenty of room to create these microelectromechanical systems—more commonly known as MEMS—with moving parts the size of bacteria. But the market for the technology has grown increasingly crowded.

Many companies are singing the praises of MEMS microphones and energy harvesters, but the fastest-growing MEMS companies are targeting RF filters and switches, a recent industry report said. The technology is proving incredibly useful for tuning antennas and routing signals through smartphones and other devices.

The report, from technology research firm Yole Développement, estimates that the MEMS market will grow from \$13 billion this year to \$25 billion in 2022. The report said that smartphone makers and others willing to pay for RF MEMS filters represent a market that will grow 35% over the next five years.

Filters, which tune into specific frequency bands and block out interference in devices like smartphones, are shuffling supplier rankings. Last year, Avago earned \$910 million in MEMS revenue, moving from the fourth to the second largest supplier of the devices behind automotive giant Robert Bosch, the report said.

Qorvo has more than quadrupled its RF MEMS sales in the last three years from \$145 million to \$585 million. The company's strategy has been to tightly integrate its switches and amplifiers inside front-ends, which also contain filters that help devices simultaneously communicate over Wi-Fi, Bluetooth, and cellular bands used in 3G and 4G networks.

These RF MEMS represent only part of the market. Last year, the third largest supplier Texas Instruments earned \$800 million in MEMS revenue, but the company's most lucrative business came from selling microscopic mirrors used in optical switches, bar code readers, and displays.

The growing number of frequency bands used for communications is increasing the number of filters inside smartphone. Luckily, MEMS

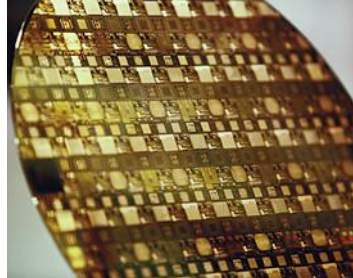
are fabricated using the same technology as traditional semiconductors, using older equipment to keep costs down and volumes up.

Eying the budgets of large smartphone makers like Apple and Samsung, several start-ups are prying into a market largely controlled by suppliers including Qorvo and Broadcom. One high watermark came when Cavendish Kinetics, an RF MEMS company, announced this year that its antenna tuners had been used in a version of the Samsung Galaxy smartphone.

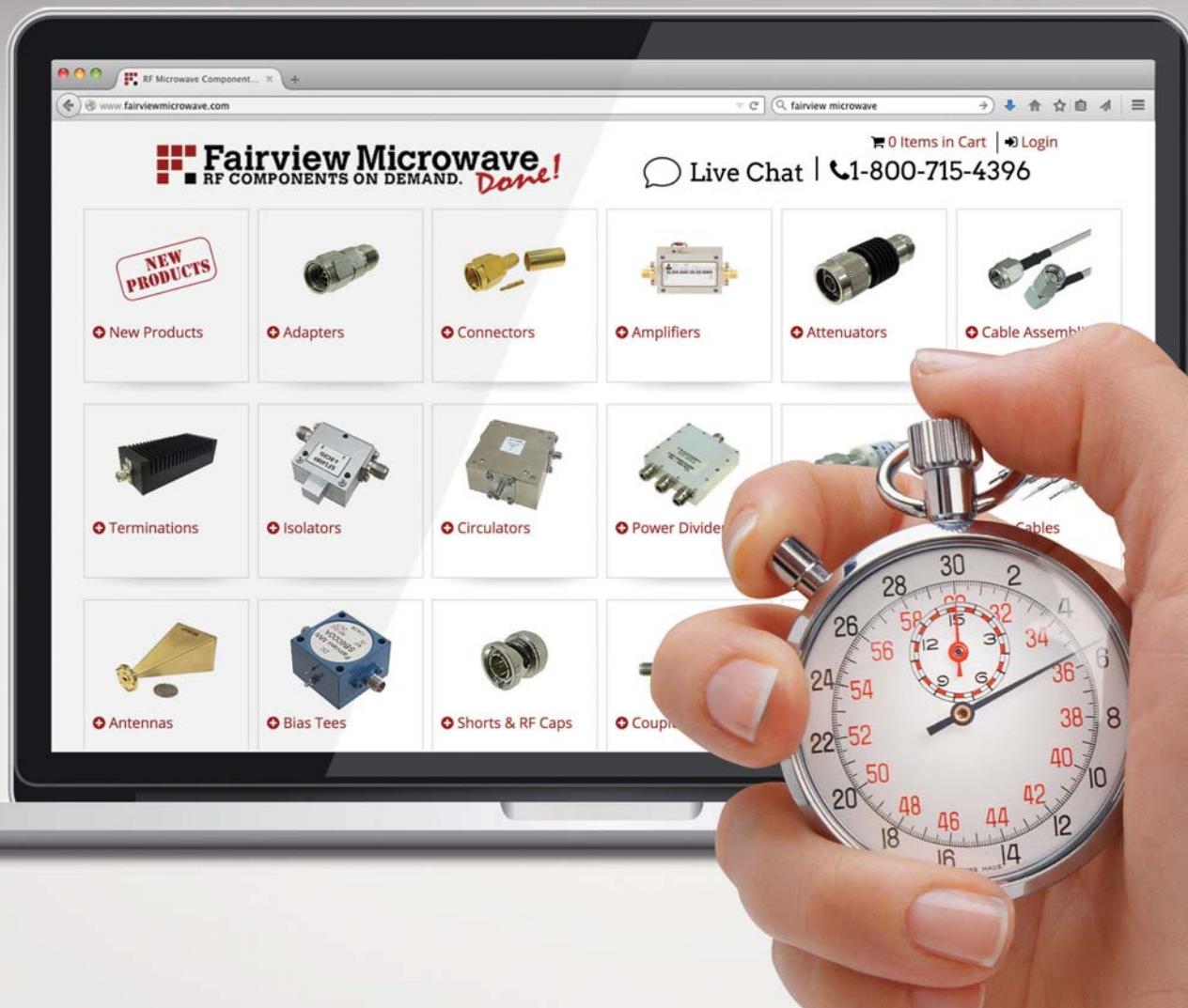
Other start-ups include Menlo Micro, a General Electric spinoff that last year released a switch that it had originally developed for remote-control circuit breakers. A smaller supplier Radiant MEMS invented switches that can survive 1.5 billion switching cycles, which is important because, unlike semiconductors, MEMS switches wear down over time.

But not every start-up has lasted living in the shadow of major suppliers. Last year, France's DelfiMEMS closed down after it ran out of funding.

Several wireless giants are probing start-ups for new technology. Both Qorvo and Qualcomm, which has a fledgling filter business, have contributed to Cavendish's \$68.5 million in funding over the last decade. The investments, experts say, highlight how badly companies want parts that better tune, filter, and direct radio signals. ■



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## IN BUYING STRAIGHT PATH, Verizon Moves Needle Toward Millimeter Waves

**THE WRESTLING MATCHES** over millimeter wave spectrum are intensifying. Major wireless carriers have acknowledged that the high frequency bands are vital for 5G communications.

That became clearer earlier this month when Verizon announced a \$3.1 billion deal for Straight Path Communications, a major holder of 28 and 39 gigahertz bands, paying twice what AT&T offered for

the company a month earlier.

Straight Path holds 133 licenses for 28 GHz spectrum and 735 licenses in the 39 GHz spectrum, which together cover the entire United States. For decades, these millimeter waves have been left dormant, with companies hewing to lower frequencies for 3G and 4G. But most companies believe that 5G will tap into both types of spectrum.

The lower bands are better at spanning long distances and penetrating buildings, but those available to be licensed are extremely scarce and expensive. On the other hand, millimeter waves are not only plentiful, but they also provide greater capacity and faster download speeds.

Both wireless carriers and chip suppliers have recoiled from higher bands because of their inherent limitations and the wide availability of lower frequencies. Millimeter waves can only travel over short distances before being absorbed by the atmosphere and they cannot pass through buildings or walls.

The Federal Communications Commission is aiming to open these underused airwaves in other ways. Last July, agency officials voted unanimously on rules that unsealed almost 11 GHz of millimeter wave spectrum above 28 GHz. The rule also opened unlicensed spectrum between the 64 GHz and 71 GHz bands.

Few options remain for licensing bread-and-butter frequency bands. AT&T said it was buying Straight Path shortly before federal regulators closed an auction of television spectrum in the 600 MHz band, one of communication's sweet spots with better range and penetration than other bands.

The boldest bidder was T-Mobile, which paid around \$8 billion for 1,525 licenses or 45% of the available spectrum, while Dish Network's \$6.2 billion returned a quarter of the licenses. AT&T, which bought FiberTower earlier this year for 24 GHz and 39 GHz spectrum, placed few bids in the auction. Verizon declined to bid at all.

Over the next 39 months, the FCC will repackage the spectrum and move broadcast stations to new channels, officially freeing up the bands. If all goes to plan, that process will end in the first half of 2020, the same year that wireless carriers plan to bootstrap the first commercial 5G networks online. ■

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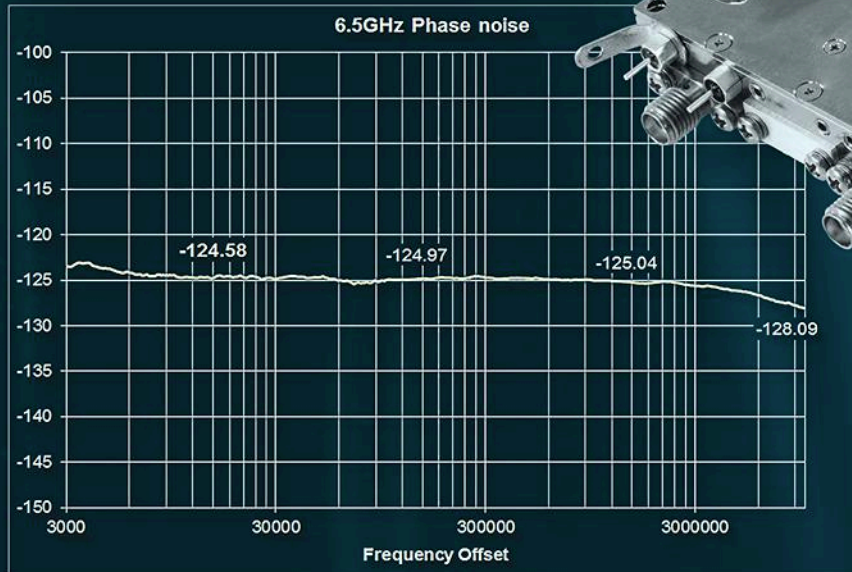
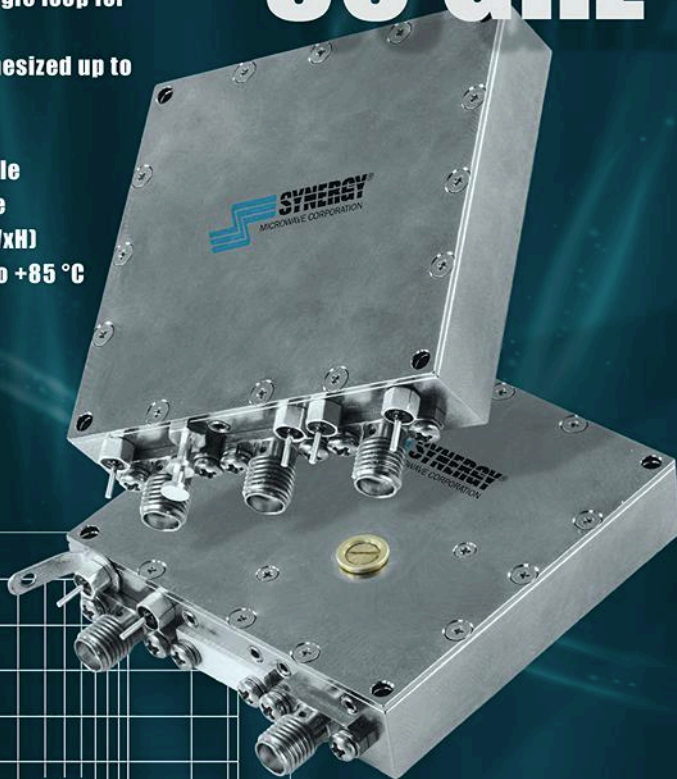
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# Inside TRACK

with

**Scott Allen**

*CMO, FreeWave Technologies*

Interview by CHRIS DeMARTINO, Technology Editor

**SCOTT ALLEN** from FreeWave Technologies shares his thoughts on topics like the Industrial Internet of Things (IIoT) and frequency-hopping spread-spectrum (FHSS) technology.

## First, can you give a brief overview of FreeWave Technologies?

With over 20 years of RF innovation under its belt, we enable military unmanned systems, original equipment manufacturers (OEMs), and industrial wireless. Millions of our outdoor, ruggedized radios have seen action in some of the harshest and dangerous places in the world, including places like the Saudi desert, South American volcano ranges, and Antarctica. Our new ZumLink IIoT Programmable Radio (IPR) platform is a real-world example of Fog Computing, machine-to-machine (M2M), and the Intelligent Internet of Things (IIoT)—not just IoT hype.

## What are some of the major IIoT applications?

As device ecosystems grow and expand, the types of data transported will diversify. With the emergence of smart sensors, our customers need to transport more than just traditional SCADA data, more than just telemetry.

We are seeing this diversification and expansion in sectors that have traditionally been SCADA only, like oil & gas, water/wastewater, and utilities. Of course, unmanned systems and OEM wireless applications are increasingly relying on edge intelligence and real-time decision making that the IIoT drives.

## Can you talk about what an IIoT network looks like today?

A modern IIoT network may have a myriad of machinery, devices, and sensors connected in a geographically dispersed network. Let's take the modern oilfield as an example. While



it contains sensors that typically transmit telemetry, like temperature, pressure, and chemical conditions, we are increasingly seeing more data-intensive applications like video, perimeter security, and smart sensors with edge-intelligence.

## How do you see IIoT networks changing in the future?

As mentioned previously, we are seeing more data-intensive application in IIoT ecosystems that will require edge-intelligence that boost real-time decision making and action. In addition, IIoT ecosystems are sending vast amounts of data to HQ or the cloud. Edge-intelligence will reduce the amounts of data required for business decisions and action, sending only the data organizations need, when they need it.

## Can you explain frequency hopping spread spectrum (FHSS) technology for those who may not know?

In oil & gas and military & government applications, FHSS is frequently used and widely known as a strong wireless communication option. However, the technology seems to be relatively unknown in IT.

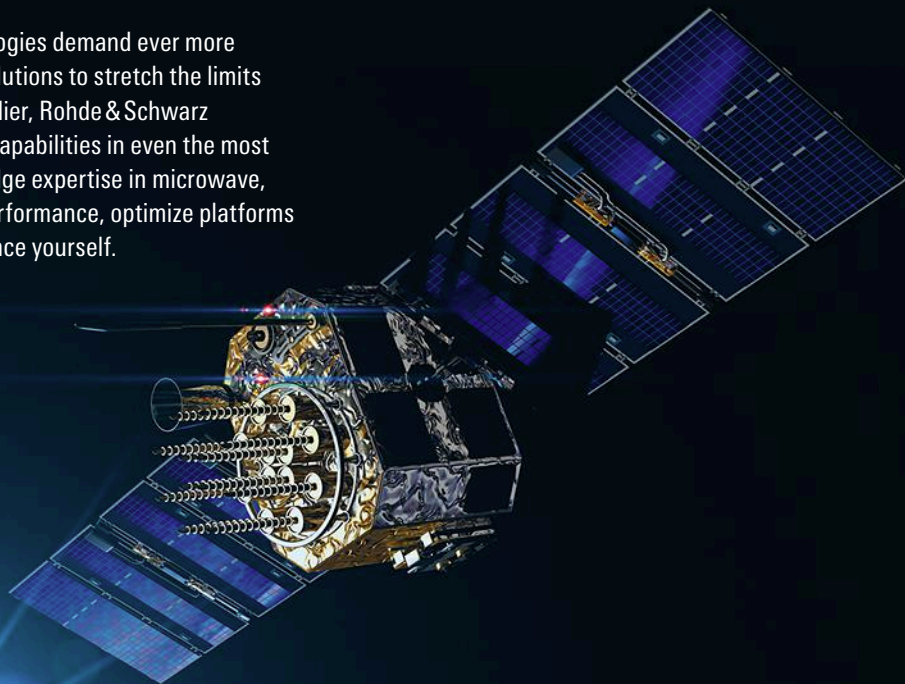
FHSS is a PROVEN wireless technology that spreads its signal over rapidly hopping frequencies. It transmits much longer distances than Wi-Fi, Bluetooth, LoRa, or ZigBee. It was invented for the security of the Free World during World War II by actress Hedy Lamar to prevent the Germans from jamming U.S. radio signals.

As such, IT decision makers must be made aware that it is a robust and inherently cyber secure means of transmitting remote field data. **ITW**

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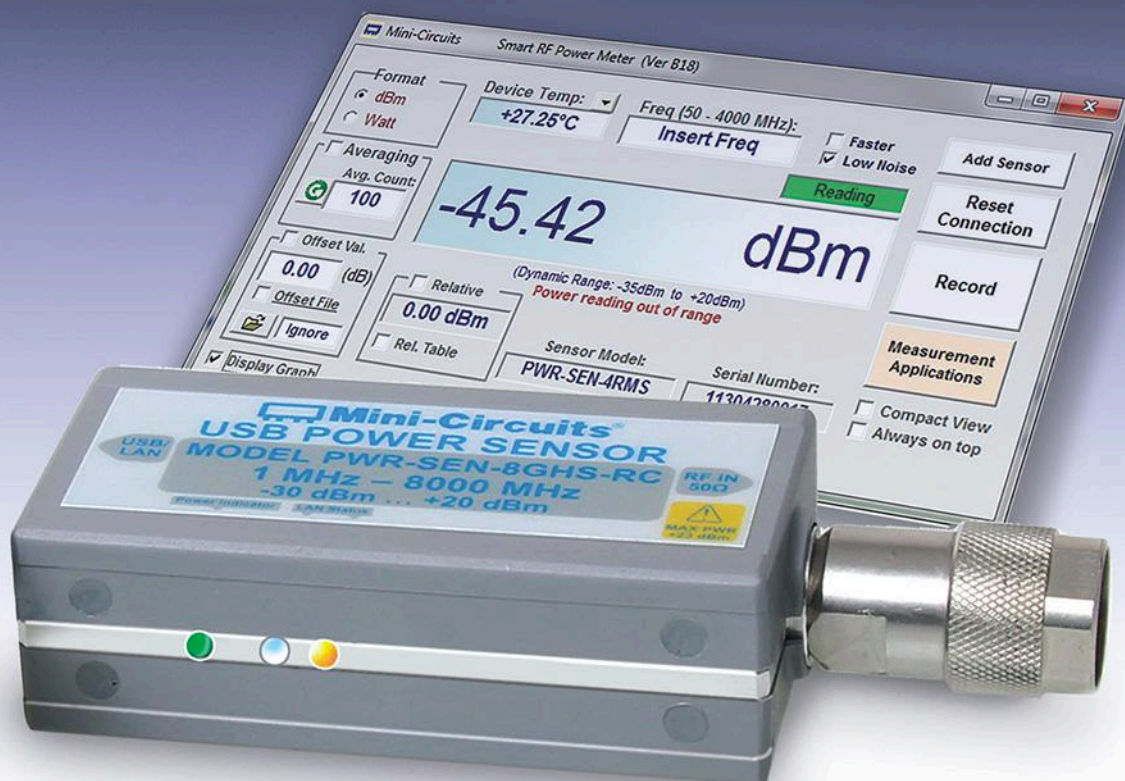
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\*Measurement speed as fast as 10 ms for model PWR-8-FS. All other models as fast as 30 ms.

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## PRODUCING EFFICIENT POWER for 5G

**A**mplifier efficiency is an important requirement for achieving cost-effective operation of any wireless network. High power-amplifier (PA) efficiency will no doubt be needed for Fifth-Generation (5G) wireless networks, and it was the focus of an investigation into the use of supply modulation or envelope tracking (ET) technology to enhance the efficiency of several different types of PAs. The research was performed by Zoya Popovic, a graduate professor with the University of Colorado at Boulder.

In a PA with ET, the power-supply voltage to the PA is dynamically varied according to the signal envelope to keep the amplifier in compression where efficiency is high. One challenge in implementing ET in a PA is maintaining broad bandwidth. In addition, supply modulation is inherently nonlinear, and additional linearization circuitry is often needed to compensate for some of the effects of the dynamic power supply. For an envelope modulator with high efficiency and large bandwidth, this implies a large slew rate. For a switch-mode power supply with pulse width modulation (PWM), high switching frequencies are needed for large bandwidths. Because of the complex impedance between the supply and the PA, a special filter is oftentimes needed to meet the envelope bandwidth requirements.

Traditional PAs with ET have been designed based on gallium arsenide (GaAs) device technology at lower (2 GHz and less) microwave frequencies. For his research, Professor Popovic chose to explore higher-frequency amplifiers based on gallium nitride (GaN) active devices—notably, those based on the Qorvo (TriQuint) 150-nm GaN on silicon-carbide (GaN-on-SiC) process. Amplifiers were first evaluated by measuring static power-added-efficiency (PAE) performance based on different supply voltages, such as +3.2 to +20 V dc for an X-band PA. These test results were used to determine a trajectory between the supply voltage and the input signal envelope so that a desired tradeoff could be achieved among efficiency, gain linearity, and output power.

Supply modulation was used to increase the efficiency of various PA architectures, including Doherty amplifiers, and ET PA designs were found to provide the best solutions for applications in which the output power was required to change over a large range, such as daytime versus night-time conditions. When sufficient ET bandwidth can be achieved, amplifiers designed with integral supply modulation can provide significant improvements in efficiency even when compared with Doherty amplifiers.

See “Amping Up the PA for 5G,” *IEEE Microwave Magazine*, Vol. 18, No. 3, May 2017, p. 137.

## MICROMACHINING FORMS 1.9-THz Silicon Antenna

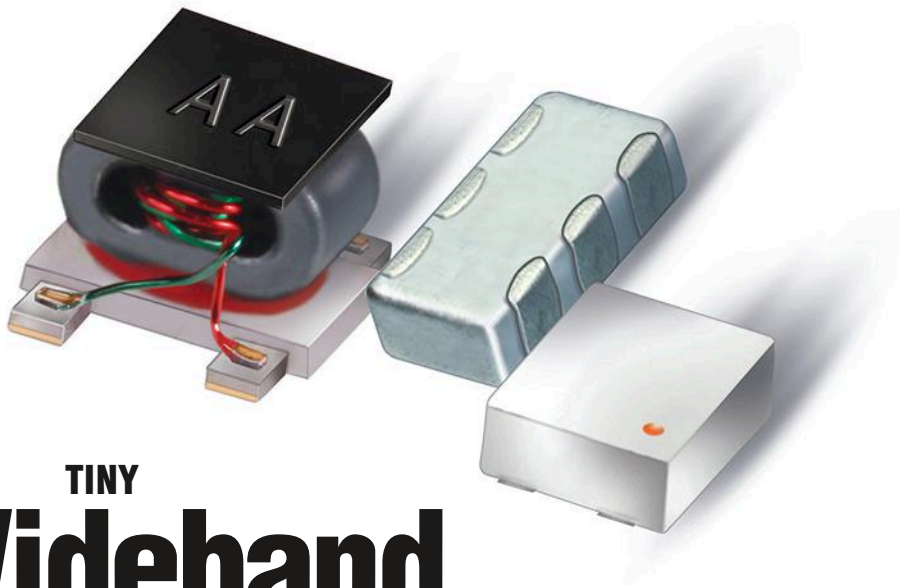
**TERAHERTZ (THz) FREQUENCIES** have been proving quite useful for research in materials science and medical analysis. The challenge is in generating and directing signals at such high frequencies without excessive loss. By using micromachining techniques on silicon wafers, researchers at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology were able to fabricate two antennas for use at 1.9 THz based on a leaky-wave waveguide feed and silicon microlens. That particular frequency is of interest for the heterodyne detection of the spectral line of ionized C+ fine structure transitions, as applied in galactic studies of dark clouds. The researchers worked under a contract from NASA, with the support of the Submillimeter-Wave Advanced Technology Group of JPL.

In constructing these antennas, the scientists were faced with the tradeoff between size and directivity: Longer horns are needed for higher directivity. The two antennas were a 2.6-mm-diameter microlens antenna with directivity of 33.2 dB and a 6.35-mm-diameter microlens antenna with directivity of 41.2 dB. The antennas were machined using deep reactive ion etching (DRIE) to form multiple-depth features with high aspect ratios on silicon wafers. The approach provides features with high precision and also enables integration of a large of a THz heterodyne receiver on a silicon wafer.

The two lenses were fabricated on different wafers, since they required different photoresist thicknesses and different silicon etch rates due to the different heights. The surfaces of the lenses were scanned to determine the accuracy of the fabrication process; they were found to achieve root-mean-square (RMS) errors in the neighborhood of 1.4  $\mu\text{m}$  for the smaller lens and 9.9  $\mu\text{m}$  for the larger lens. Measurements on the two antennas were made using a 1.9-THz transmitter chain starting with a 17-GHz frequency synthesizer feeding a commercial multiplier to reach 105.5 GHz.

The multiplier's output signals were boosted by a WR-10 power amplifier and then doubled to produce signals at 211.1 GHz. A tripler transformed those signals to output signals at 633.3 GHz and 2 mW, which was fed to a tripler on a silicon wafer stack to yield 800 nW at 1.9 THz. A bolometer was used for the power measurements. The researchers were encouraged by the test results, which included radiation efficiencies of 70 and 60%, respectively, for the smaller and larger lens antennas. Future work will target the development of larger antennas with less surface defects and more precise curvature.

See “Development of Silicon Micromachined Microlens Antennas at 1.9 THz,” *IEEE Transactions on Terahertz Science and Technology*, Vol. 7, No. 2, March, 2017, p. 191.



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# BLE Antenna Testing Helps Optimize IoT Device Performance

Two companies have partnered to unleash an over-the-air (OTA) antenna measurement system for Bluetooth Low Energy applications.

**M**any new Internet of Things (IoT) devices rely on wireless technology as their primary or only method of communication. Tight constraints on power, size, and cost make it very challenging to design and manufacture devices with good RF (wireless) performance, though. Particularly challenging is antenna performance, because its small size and close proximity to other components create problems in achieving good impedance matching and a good isotropic antenna radiation pattern.

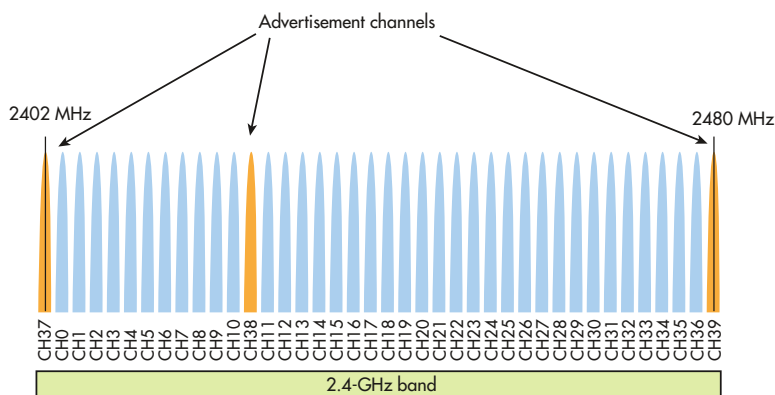
Characterizing this antenna performance requires specialized over-the-air (OTA) measurement techniques that, until recently, have not been available for Bluetooth Low Energy (BLE) technology. To meet that need, ETS-Lindgren ([www.ets-lindgren.com](http://www.ets-lindgren.com)) and LitePoint partnered up to produce the first BLE OTA antenna measurement system. This article describes how BLE antenna measurement can optimize device performance to boost customer satisfaction.

To validate how well a device's antenna is expected to perform in a real-world application, engineers typically use total radiated power (TRP), total isotropic sensitivity (TIS), and antenna radiation patterns in vertical and horizontal polarization to characterize and compare device performance. The transmitter measurements indicate how much total RF power the device transmits and how evenly this power is distributed around a far-field sphere. Similarly, the receiver measurements determine the total integrated sensitivity while receiving RF signals

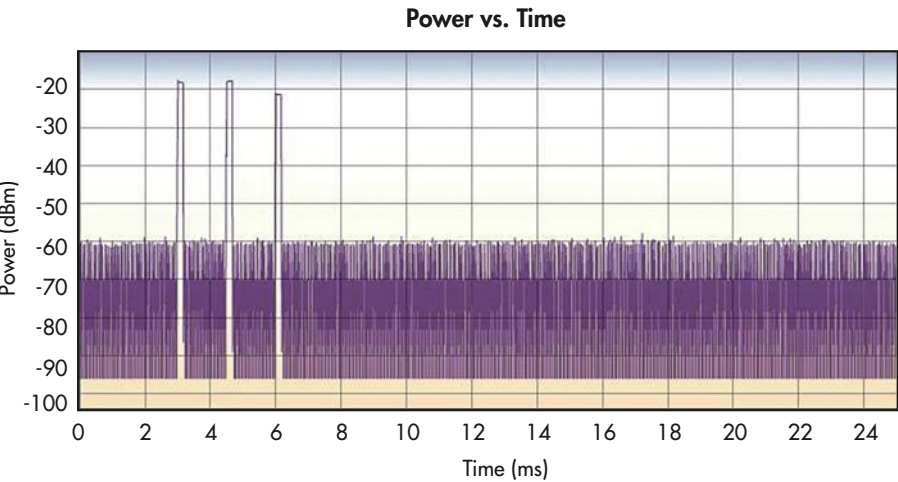
from all directions. These measurements, which have been used effectively for many years with cellular and Wi-Fi technologies, recently became available for BLE devices.

## GOING OVER THE AIR

By applying properties of all BLE devices, engineers can leverage an OTA test solution to quickly and accurately measure BLE transmitter power and receiver sensitivity. BLE devices all transmit on specific RF frequencies, known as advertising channels, as a beacon to other BLE receivers (*Fig. 1*). These advertising channels are well-distributed across the entire 2.4-GHz band, at frequencies of 2402, 2426, and 2480 MHz. Using these three channels to characterize RF performance provides engineers with high confidence that the device is working effectively across the entire band.



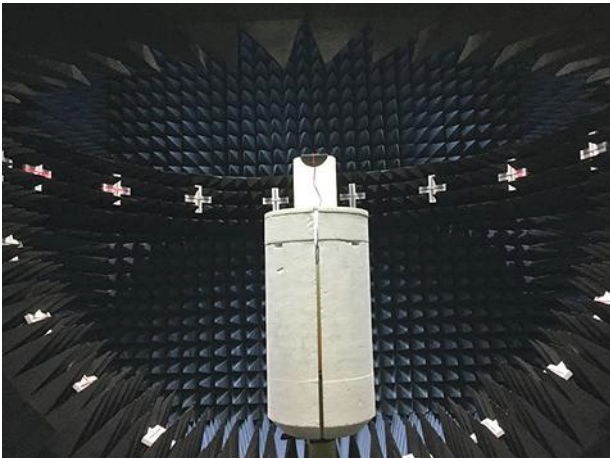
1. BLE utilizes advertising channels at frequencies of 2402, 2426, and 2480 MHz.



2. This figure illustrates three rapidly transmitted advertisements.

When a BLE device “wakes up,” it will rapidly transmit advertisement packets on all advertising channels within a period of a few milliseconds. *Figure 2* shows a power-versus-time capture that illustrates the three advertisements in rapid succession. If, during this time, the device does not receive any requests from other devices, it will go back to sleep and repeat this process a short while later—typically within 1 to 10 seconds. This BLE characteristic can be used to rapidly and accurately measure transmitter output power on these three RF channels.

Using an anechoic chamber with multiple antennas positioned in a ring and a movable pedestal that holds the BLE device, these transmitter measurements are performed at various positions around a 360-degree sphere. *Figure 3* shows an anechoic chamber, ring antenna, and pedestal with a BLE device mounted on top.

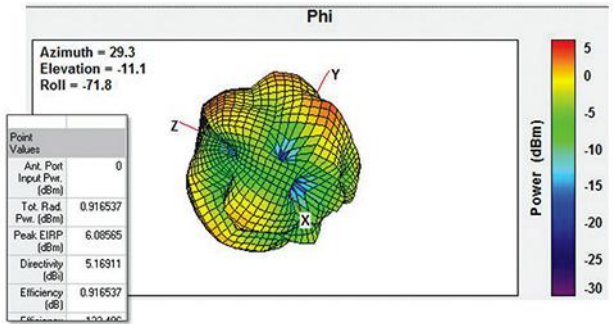


3. Transmitter measurements are performed in an anechoic chamber to determine the transmitter radiation pattern.

These transmitter measurements are performed at 15-degree increments, creating an accurate representation of the transmitter radiation pattern. By applying calibration data and integrating results from all measurements, the TRP is calculated to determine how much power the device is transmitting. In an ideal case, the antenna would be 100% efficient and all power from the device would be radiated outward.

Also, because a mobile device transmitter doesn’t know the direction of the receiving device, the ideal antenna pattern is typically “isotropic”—meaning that it radiates equally in all directions. Of course, getting to the ideal radiation pattern and TRP is the goal. But realistically the antenna cannot be 100% efficient; the antenna pattern will inevitably have some nulls.

With an OTA measurement system, engineers can easily characterize their device, make design improvements, and then rapidly evaluate the impact of those changes. *Figure 4* shows an antenna radiation pattern and TRP results from an actual BLE device.



4. This antenna radiation pattern and TRP were the result of an OTA test on a BLE device.

RECEIVER SENSITIVITY

Receiver sensitivity is always a more complex and more time-consuming measurement. But it is just as critical as transmitter performance, and is characterized using a similar method. Whenever a BLE device transmits an advertising packet, it listens for a brief period of time to determine if other BLE devices are trying to communicate with it. During this short but precise time, an OTA test solution

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With a BLE OTA testing solution, engineers get clear visual and parametric insights into how their designs are performing, and can use this knowledge to improve and optimize performance to ensure customers have the best possible user experience.

may send a special Bluetooth message on the advertising channel, known as a scan request, to determine if the BLE device can receive the message from the tester.

If the device does receive the message, it acknowledges the scan request with a scan response message. This "ACK" message from the BLE device indicates the receiver properly received the packet. The test system sweeps the RF power through a range of different levels to determine the minimum point where the BLE device can reliably receive packets.

This methodology of using advertising packets, scan request, and scan response messages allows the test system to accurately measure the BLE device packet-error-rate (PER) at various RF levels and determine receiver sensitivity. Just like the transmitter measurements, receiver performance is measured at a variety of positions around the sphere. The TIS is calculated using calibration data and integration of all measurement results. *Figure 5* shows a receiver antenna pattern and TIS from an actual BLE device.

A far-field anechoic chamber has very high RF path losses. The calibration of this chamber and the associated components is a critical part of making accurate RF measurements. To calibrate the chamber, a calibrated dipole radiator with known performance is placed on the pedestal where the BLE device will be positioned. The calibrated radiator is used to measure path loss between the "testing position" and the measurement ring that contains both horizontal and vertical measurement antennas.



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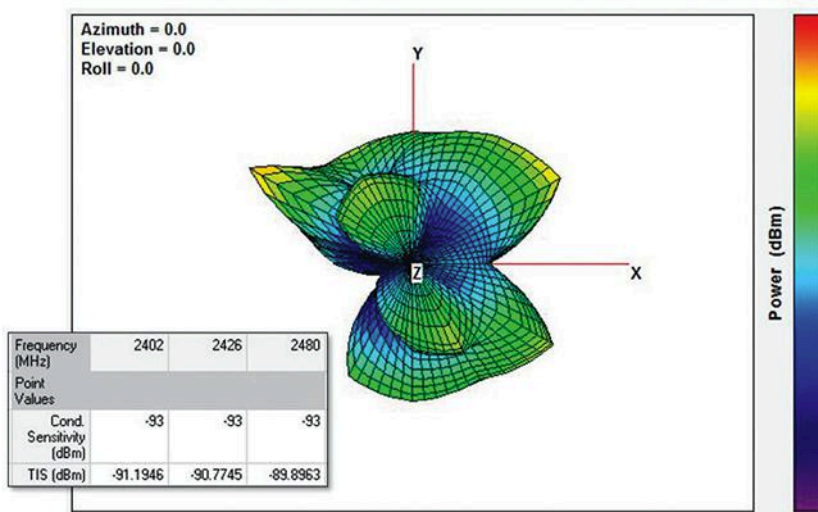
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In addition to losses due to the OTA distance, switches, RF cables, and RF amplifiers are characterized as part of the system calibration. This careful attention to detail allows typical BLE measurements to have about 2-dB measurement accuracy—although achieving better accuracy is possible using more measurements and, therefore, longer test times.

For IoT, if the wireless technology doesn't work well, the device doesn't work well and customers won't be satisfied. With a BLE OTA testing solution, engineers get clear visual and parametric insights into how their designs are performing, and can use this knowledge to improve and optimize performance to ensure customers have the best possible user experience. With powerful and easy-to-use test solutions, engineers can focus their expertise on improving their design and getting products more rapidly out of the lab and into the market. **MW**



5. An OTA test on an actual BLE device produced this receiver antenna pattern and TIS.

ALLEN HENLEY is senior product manager at LitePoint, a leader in wireless test and measurement. He is focused on driving product strategy and definition for new products in Cellular, WiFi, and Bluetooth, as well as other IoT technologies.

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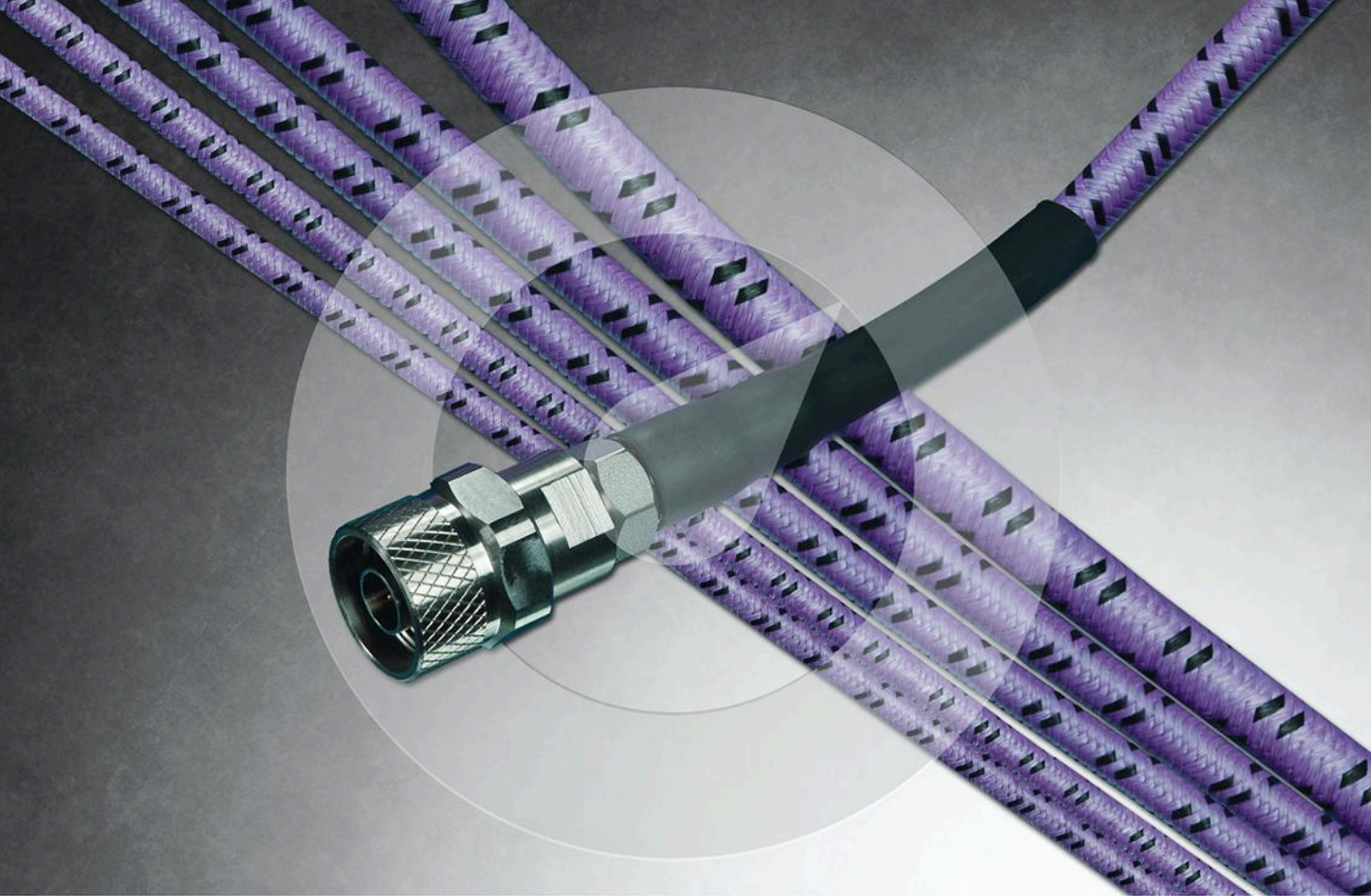
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# Measurements Help Minimize EMI and RFI

Electronic energy is widespread in most operating environments, and circuits must be designed so that they don't add to the totals—or succumb to the interference.

**ELECTRONIC DEVICES OPERATE** in a world of electromagnetic (EM) fields of various strengths. Each device is not only subject to interference from those EM fields, but may itself be a source of EM interference to other devices. EM interference can be conducted or radiated, either degrading or disrupting the performance of an electronic device.

Lower-frequency EM interference, such as from power lines, is usually referred to as electromagnetic interference (EMI). Higher-frequency EM interference, such as from radio waves, is known as radio frequency interference (RFI), although the two terms are often used interchangeably. Electromagnetic compatibility (EMC) refers to the fact that an electronic device has been found to operate effectively in this world of EM fields, not causing interference and not affected by the interference around it.

EMI/RFI can be conducted or radiated, and even the most well-conceived circuit layouts can fall prey to their effects. But by the use of software design tools and by performing EMI measurements throughout the design process, it is possible to avoid the frustration of repeated design cycles in pursuit of EMC.

Sources of EMI and RFI are everywhere. EMI is typically generated by fast switching electronic devices, such as switch-mode power supplies, that produce harmonic signals that propagate along the conductors of an electronic device. They can appear in the forms of common-mode noise (where it propagates on multiple conductors at the same time and in the same direction) or differential mode noise (where it travels along opposite directions on signal and ground lines).

Design engineers coping with the modern demand for continued circuit miniaturization and hoping to achieve EMC compliance must create compact circuits that not only function properly while surrounded by external sources of EMI and RFI, but themselves do not generate EMI and RFI. To understand if an electronic device is a source of EMI and RFI, its own emissions must be measured across a wide enough frequency range so that several harmonic frequencies are included.

A DUT's power supply and power circuitry can be a source of conducted EMI, while higher-frequency components (e.g., oscillators and transmission lines) can function as antennas

and produce unintended RFI emissions. Some levels of EMI and RFI will be present in almost every electronic device. But through well-designed circuit layouts, proper grounding, and shielding (when necessary), those levels can be minimized.

The other side of EMI/RFI is determining a device's immunity to interference—essentially, its capability to function properly in the presence of certain known levels of EMI and RFI. A device's tendency to malfunction in their presence is known as its susceptibility. Because the use of radio frequencies varies from region to region around the world, different levels of EMI and RFI at different frequencies can cause disruptions in a device's performance depending upon the region, and different measurement procedures are developed to establish EMC compliance for each region.

Of course, by performing EMI/RFI measurements and software simulations during various stages of the design process, it is possible to know more about a circuit's tendency to perform as an emitter as well as its susceptibility to other sources of EMI and RFI. Failing an EMC compliance test can be costly, resulting in time-consuming rework of a circuit layout without a guarantee of passing the next test.

## EARNING EMC

The process of achieving EMC for an electronic design involves preventing the negative effects of EMI through EM simulation and exacting measurements. Whenever possible, EMC is a goal that should be reached with the minimum number of additional components (EMI filters and connectors, for example) and few additional materials (such as shielding gaskets). At times, however, these additional components and materials cannot be avoided for full EMC.

Once a manufacturer is confident that an electronic design can meet the EMC requirements for a particular region, the design must pass the regulations for a particular market region. Australia, Canada, the European Union (EU), and the United States each have their own regulations for EMC. Internationally, the International Electrotechnical Commission (IEC; [www.iec.ch/emc](http://www.iec.ch/emc)) is one of three global organizations concerned with worldwide EMC standards for measurement of EMI and

RFI, along with the International Standards Organization (ISO; [www.iso.org](http://www.iso.org)) and the International Telecommunication Union (ITU; [www.itu.int](http://www.itu.int)). The Comité International Spécial des Perturbations Radio (CISPR, or the International Special Committee on Radio Interference; [www.iec.ch](http://www.iec.ch)) is an organization within IEC devoted to analyzing and combatting RFI, essentially at frequencies above 9 kHz.

In the U.S., regulations for EMC are set largely by the FCC, with different rules applying to different types of products. For RF products, the FCC's Code of Federal Regulations (CFR), Section 47, Part 15 rules for unintentional radiators apply, although Section 47, Part 18 rules are used for equipment operating in industrial-scientific-medical (ISM) frequency bands. In the U.S., medical equipment is exempt from FCC rules for EMC and is controlled by standards set by the Food & Drug Administration (FDA, [www.fda.gov](http://www.fda.gov)) and defense-electronics equipment must meet demanding military standards, such as MIL-STD-461E and MIL-STD-464.

### MEASURING INTERFERENCE

Measurements for EMI/RFI seek to determine if a device is a source of EM radiation or if it is susceptible to the EM fields around it. In both cases, measurement equipment must be highly sensitive in order to detect low levels of EM. At the same time, it must be highly accurate, so as to comply with highly detailed test requirements established by the various EMC standards organizations. Programmability and the use of measurement software can speed and simplify the process, storing settings that are repeatedly used as part of standards-based measurements.

Testing for EMI and RFI emissions or immunity requires a number of different tools in addition to a shielded test environment. These include a test receiver or analyzer with suitable bandwidth and sufficient sensitivity to detect low-level signals; a line impedance stabilization network (LISN) connected to a DUT for measuring conducted emissions; a signal generator to provide the types of interference expected; and an antenna or EM field probe for measuring radiated emissions. Depending upon the EMC compliance tests required, additional hardware may be needed, such as high-power amplifiers to boost test signals to power levels defined by the compliance standards.

For EMI and RFI immunity testing according to IEC standards, for example, a test system would require a test receiver or analyzer, a signal generator, a power meter, a power amplifier, and a test antenna. The instruments should all cover a fre-

quency range of interest for a particular DUT, and the signal generator should be capable of producing the various modulation formats—e.g., amplitude modulation (AM) and pulse modulation—that are defined in a particular IEC standard. The test analyzer or receiver should provide a wide dynamic range, with low noise floor and high sensitivity to detect low-level signals; a high-enough intercept point to handle higher test power levels; and suitable bandwidth to meet the requirements of a particular standard.

For the number of measurements required, a candidate EMI receiver should provide high-speed testing, but it also must be highly accurate in compliance with applicable EMI standards. It should be characterized by extremely low displayed average noise level (DANL) and provide the analysis bandwidths needed for the EMI tests.

The N9038 MXE EMI receiver from Keysight Technologies ([www.keysight.com](http://www.keysight.com)) is an example of such an instrument, with versions covering frequency ranges of 3 Hz to 3.6, 8.4, 26.5, and 44 GHz. It provides all the CISPR analysis bandwidths and delivers a typical DANL of -160 dBm, with a generous assortment of preselector filters and a built-in preamplifier for low-level troubleshooting.

This is one example of the excellent EMI receivers on the

market, from such suppliers as AFJ Instruments, ETS Lindgren, HV Technologies, Rohde & Schwarz, and Wavecontrol S. L. Rohde & Schwarz ([www.rohde-schwarz.com](http://www.rohde-schwarz.com)), for example, offers a variety of EMI test receivers, for both precompliance and full compliance testing. The company's ESR test receiver combines an EMI receiver and real-time spectrum analyzer in one package, with versions covering frequencies of 9 kHz to 3 GHz and 9 kHz to

6 GHz. And for those who want to leave the testing to someone else, companies are available for performing EMI site surveys as well as compliance testing to many international standards, such as F2 Labs ([www.f2labs.com](http://www.f2labs.com)) and Keystone Compliance ([www.keystonecompliance.com](http://www.keystonecompliance.com)).

Prior to testing, a great deal of time can be saved in the design process through the use of software tools, notably EM simulation software that can model the expected EM behavior of a high-frequency circuit prior to assembling a prototype for the first time. Both 3D EM simulation tools and mathematics-based modeling tools can use a computer to predict where disturbances from EMI and RFI will occur, allowing a user to make modifications to the design in search of a solution prior to assembling a circuit. **mw**



**This series of EMI receivers includes models with frequency ranges to 44 GHz and all standard CISPR analysis bandwidths, shown with typical DANL of -160 dBm. (Courtesy of Keysight Technologies.)**

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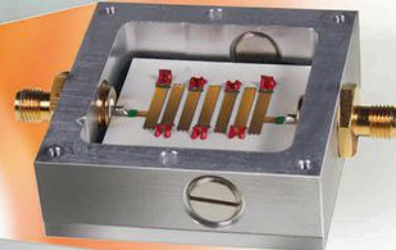
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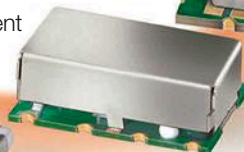


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# Additive Manufacturing Enables Microwave Components for Space Applications

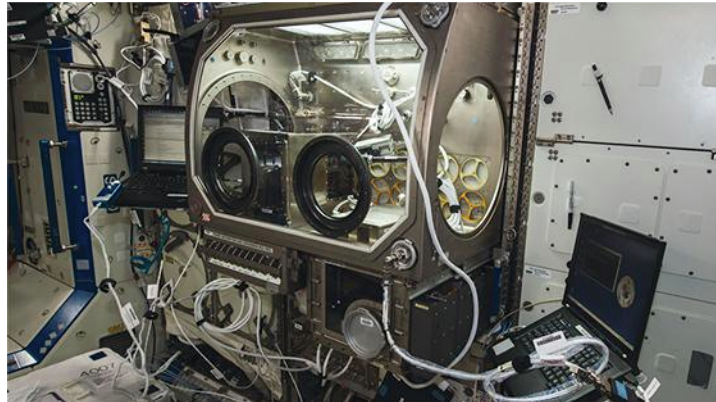
Additive manufacturing techniques can be used to build RF/microwave components for demanding space applications, offering benefits like reduced mass.

**ADDITIVE MANUFACTURING, ALSO** known as 3D printing, enables the fabrication of objects through the deposition of material in order to obtain fit-for-purpose hardware. This differs from traditional subtractive processes, where material is removed from larger, semi-finished products. Like many new manufacturing processes, 3D printing arose from the merging of previously existing technologies: The coming together of computer-aided-design (CAD), inkjet nozzles, and automated machine systems.

Additive manufacturing includes a large family of processes and technologies and can be applied to a wide range of materials—ranging from metals and polymers to ceramics—as well as food, living cells, and organs. Today, AM is a standard manufacturing process in a significant number of industrial applications and high potential is anticipated (and in many cases, already demonstrated) in high-end technology sectors, including aerospace, turbine industries, and medical applications.

Additive manufacturing can also be adopted for in-orbit manufacturing onboard the International Space Station (ISS) for both plastics and metals. NASA has a plastic 3D printer on the ISS today (*Fig. 1*). In February 2016, the European Space Agency (ESA) and the Italian Space Agency (ASI) successfully proved on the ISS the “Portable On-Board Printer 3D” (POP3D; *Fig. 2*), as a technology demonstration for long-term manned exploration missions.

As on the ISS, manned missions could carry 3D printers to ensure full self-reliance, as they fly for months or years from Earth with limited resources. No need to bring a significant amount of spare parts (which will probably never be used): A large spare parts stock can be replaced with a printer and powders of most common materials to be printed if necessary into



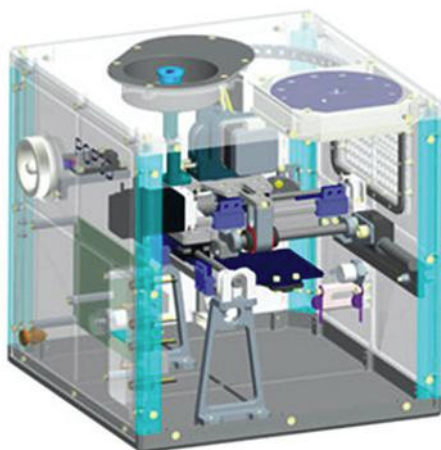
1. This image shows a 3D printer in the Microgravity Science Glovebox onboard the ISS.

the failed part. Alternately, on-demand tools can be manufactured in-situ to disassemble and fix malfunctioning units.

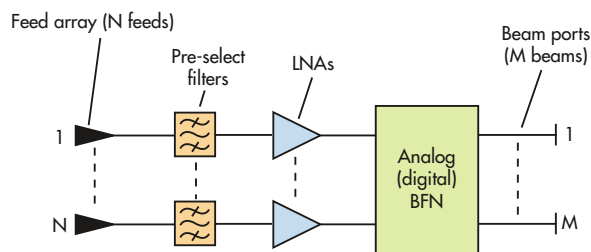
Industrial manufacturers of mechanical components for on-board space applications are catching onto additive manufacturing. 3D printers are already used for the realization of mechanical and structural parts for space applications. Less obvious so far has been the use of 3D printers to manufacture passive microwave components and assemblies.

The European Space Agency, through development contracts with a number of European industries, has been pioneering the application of additive manufacturing for the production of microwave components. The adoption of this new manufacturing technology for the production of RF space components is justified by the increasing complexity of satellite payloads.

2. This is an illustration of the POP3D, which was demonstrated successfully by the European Space Agency and the Italian Space Agency.



Future satellite communications payloads will require an ever-higher degree of flexibility in order to cope with evolving mission requirements and to allow reconfigurability, both in terms of traffic distribution and ground coverage. Active array antennas, either in the form of direct radiating arrays (Fig. 3) or that of array-fed reflectors, offer a high degree of reconfigurability in terms of traffic distribution and antenna footprint, while maintaining a full and effective freedom in the allocation of the available resources (e.g., RF power per beam in the TX section).



3. A simplified block diagram of an active direct radiating array antenna is shown here.

A satellite multi-beam active antenna is a rather complex subsystem that includes active components (low-noise amplifiers and power amplifiers) together with a high number of passive parts and components. This integration includes arrays of radiating elements, polarizers, filters, waveguide runs, couplers, and power dividers.

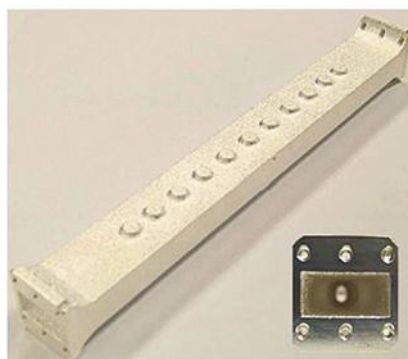
The possibility of integrating in the same assembly different passive microwave components (e.g., feed arrays, beam-forming-networks, or filters) is particularly important in modern satellite payloads, often including complex multi-beam antennas. In these cases, the reduction in payload mass and cost can be dramatic. Mass reduction, optimization of the occupied volume, and mechanical interface reduction are very important in space applications, where mass and volume are

In terms of mass, it is worth noting that, while electronic devices lend themselves to miniaturization, electromagnetic structures (such as microwave filters) are strongly constrained by the laws of physics (e.g., wavelength, current densities, conductivity, and Q-factor).

critical. Moreover, the high number of interconnections and the complex waveguide routing can lead to problems in terms of passive intermodulation (PIM), thus limiting the power handling capability in multi-carrier regimes.

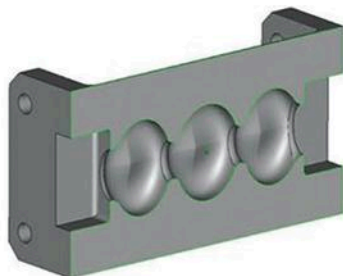
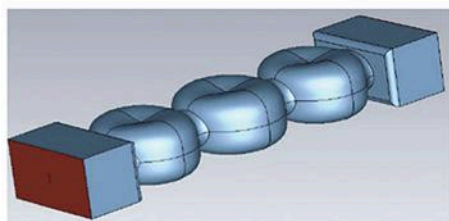
In terms of mass, it is worth noting that, while electronic devices lend themselves to miniaturization, electromagnetic structures (such as microwave filters) are strongly constrained by the laws of physics (e.g., wavelength, current densities, conductivity, and Q-factor). The application of additive manufacturing technologies to RF and microwave passive components has already proven a potential reduction of up to 50% in mass and more than 40% reduction in production time.

The European Space Agency is promoting in Europe a number of R&D activities on additive manufacturing of RF/microwave components and assemblies. One specific additive manufacturing technique, Selective Laser Melting (SLM), was applied to the implementation of bandpass filters, with the aim of reducing losses (high effective filter resonator Q) and achieving high dimensional accuracy (Fig. 4).



4. This bandpass filter was built by Selective Laser Manufacturing techniques.

With additive manufacturing, high-quality aluminium parts can be produced with an approach known as additive layer manufacturing (ALM). Using this technique, single-piece microwave components made from aluminum—including filters, couplers, and waveguide runs—were produced.



5. Additive Layer Manufacturing can be used to build microwave filters.

RF filters have been produced using optimized internal designs, where the sharp edges generated by the milling processes used so far have been replaced by performance-optimized smooth surfaces, which have tremendously simplified (and improved) the silver coating process required to further enhance RF characteristics. Mass has been reduced by 50% and the need for assembly is avoided, as the part is now manufactured in one piece (Fig. 5).

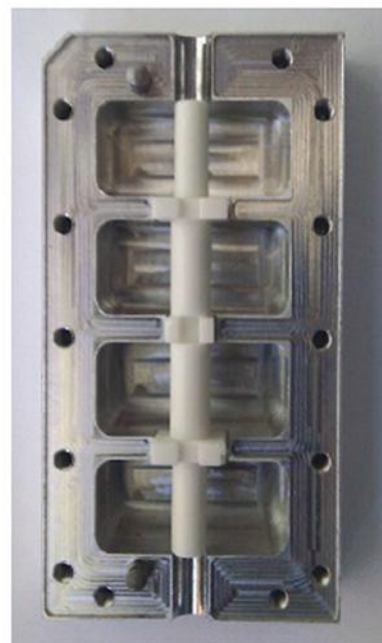
More sophisticated additive manufacturing techniques actually allow passive microwave components, such as waveguide runs and filters, to be composed mainly of plastic (e.g., in a honeycomb structure). A final layer of highly conductive

material (gold or silver, for instance) is then deposited onto the plastic core of the component, thus achieving the required electromagnetic (EM) performance.

Complex single-piece components can be produced in a short time and at a cost that is not only affordable, but also almost entirely independent of the number of items being produced. Moreover, almost arbitrary geometries and highly integrated assemblies can be realized, something otherwise difficult or impossible to obtain with traditional milling machine techniques.

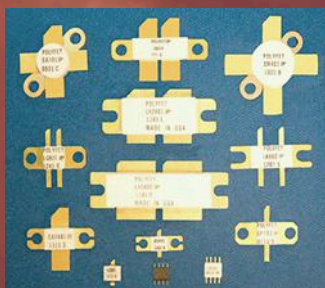
Other promising additive manufacturing technologies being developed in Europe for future satellite missions (mostly at higher microwave frequencies) are ceramic 3D stereo-lithography and Surface Integrated Waveguide (SIW) technology, which could achieve mass and size reductions of up to 30% as compared to traditional mechanical structures. These technologies could be particularly suited for active antennas applications since they would also make filters easier to integrate into active modules.

Ceramic 3D stereo-lithography is a rapid prototyping technique used to fabricate 3D ceramic structures. As such, it can be advantageously adopted for the realization of RF and microwave components



6. Ceramic 3D stereo-lithography is a rapid prototyping technique that can be used to build RF/microwave components.

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and antennas, with high dielectric constant ceramic materials. The technique can be, for instance, used to manufacture a dielectric resonator, its support, and its surrounding cavity (Fig. 6).

3D-printed antenna prototypes were developed for ESA by the Swiss company SWISSto12, employing a special copper-plating technique to coat the complex shapes. Figure 7 shows a complete antenna assembly. It incorporates a corrugated

feedhorn and two reflectors—printed all-in-one in a polymer material—and then plated with copper to meet its RF performance requirements.

SIW technology aims to realize planar microwave cavities buried in a high dielectric constant ceramic substrate (e.g., alumina), by means of via-holes defining patterns of any shape. This technology tries to reach a compromise between traditional non-planar (waveguide or coaxial, for instance)

filter structures, offering high Q factors but being difficult to integrate with active devices, and planar filter structures (e.g., microstrip), which are lower in Q but easy to integrate into active components.

With this approach, a non-planar waveguide structure can be trans-

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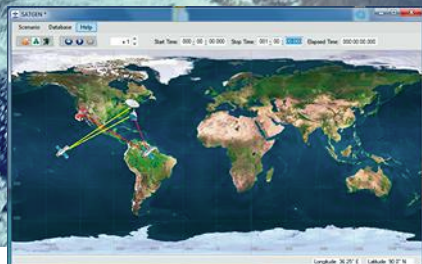
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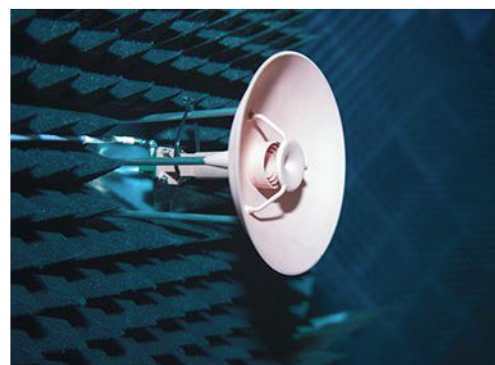
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7. This image shows a 3D printed ceramic antenna assembly.



8. This is an artist's impression of a "moon village."

formed into planar form and it can then be integrated into any planar dielectric substrate together with (for example) MMIC devices. The technology is particularly suited for applications at higher microwave frequencies (Ka-band and above).

To summarize, the specific advantages of additive manufacturing techniques for space-borne microwave components and assemblies are:

- Quick turn-around of early prototypes
- Reduced delivery times in production
- Mass reduction
- High assembly integration
- Interfaces (flanges, connectors, cables, or waveguide runs) reduction
- Overall cost reduction.

Finally, additive manufacturing is likely to play an enabling role in future planetary exploration missions, such as the “Moon Village,” the idea set forth by ESA of a village on the Moon built by huge 3D printers and inhabited for months at a time by teams of astronauts (Fig. 8). In that perspective, replacement or new microwave components will be literally “e-mailed” from Earth and then 3D printed on site. **mw**



**3** D-printed antenna prototypes were developed for ESA by the Swiss company SWISSto12, employing a special copper-plating technique to coat the complex shapes.

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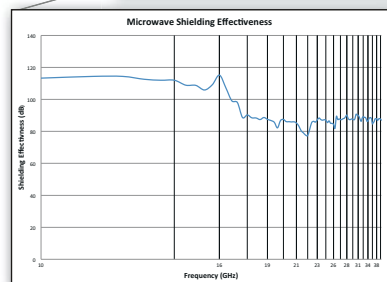
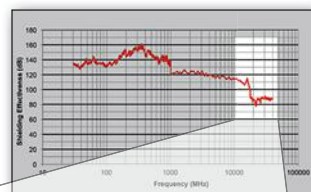
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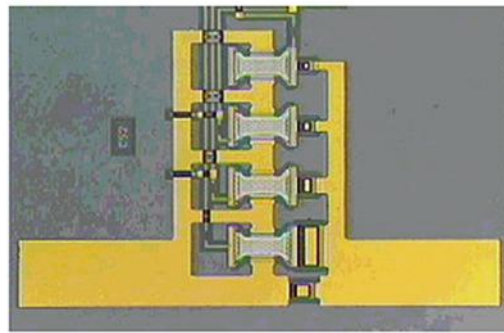
# Forming Low-Impedance MEMS Bandpass Filters

Several resonator design architectures were developed to achieve the lower input and output port impedances needed for modern wireless communications applications.

**B**andpass filters based on microelectromechanical structure (MEMS) technology potentially offer reliable electrical performance in small sizes. MEMS bandpass filters can be manufactured in several ways and, to compare two methods, filters were developed using single-annular-resonator (SAR) and soft mechanically-coupled-annular-resonator (MCAR) modules. The prototypes had center frequencies at 850 MHz and 2.4 GHz and featured close agreement between their simulated and measured characteristics. The main difference in the two MEMS filter approaches is the wider bandwidth provided by the soft MCAR filters.

Bandpass filters with small sizes have been produced in a number of ways, including with piezoelectric techniques and with capacitor arrays. The use of piezoelectric components, such as crystals and film bulk acoustic arrays (FBARs), yield high quality-factor (Q) bandpass filters as used in cellular telephones. However, the frequency of a piezoelectric component is determined primarily by its thickness, making it difficult to achieve multiband filters on the same chip without separate structural film depositions. In addition, FBAR filters are usually bulky compared with MEMS filters, which may limit their use in future mobile communications applications.<sup>1</sup>

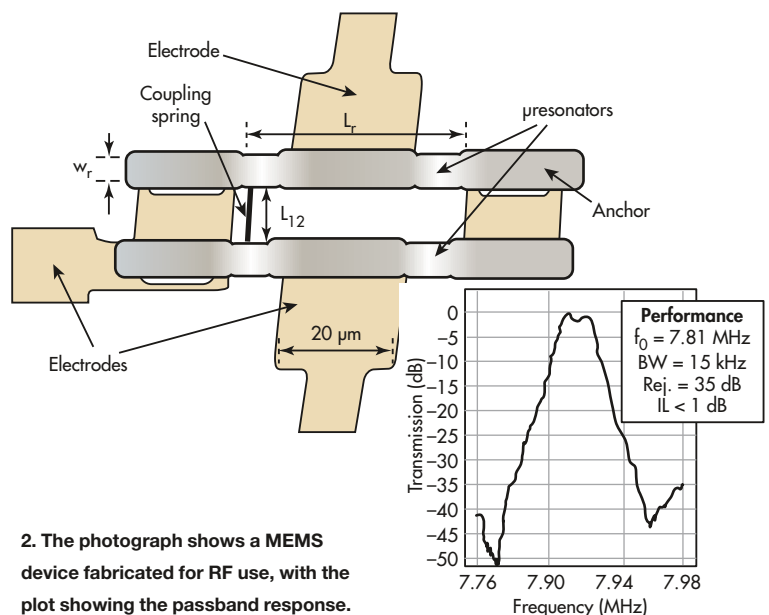
MEMS capacitive membrane switches have been used in bandpass filters covering 110 MHz to 2.8 GHz (Fig. 1).<sup>2</sup> Variable capacitor structures



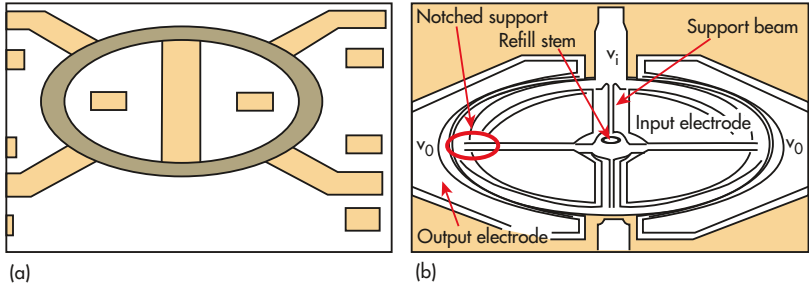
1. This photograph shows a miniature variable capacitor.

have been employed in multipole lumped-element bandpass filters, but the passband insertion loss has been between 6.6 to 7.3 dB through 2.8 GHz, which is not acceptable for modern wireless communications applications. This design technique also suffers low Q and requires a space-consuming inductor.<sup>2</sup>

High Q bandpass RF filters using MEMS oscillators have also been explored by various researchers. They are usually compact in size and require few components with lower cost than traditional filter designs.<sup>3</sup> Figure 2 shows a typical filter fabricated with this technique.<sup>4</sup> The approach yields passbands around



2. The photograph shows a MEMS device fabricated for RF use, with the plot showing the passband response.



3. Two research groups explored the possibility of designing low-impedance MEMS filters using RBAR technology, from (a) ref. 3 and (b) ref. 5.

not suitable for modern communications applications.<sup>6</sup>

To achieve low-impedance RF bandpass filters, original research was performed by

8 MHz with  $Q_s$  from 40 to 450 (percent bandwidths from 0.23% to 2.5%). Passband insertion loss is less than 2 dB, with spurious-free-dynamic-range (SFDR) performance of 78 dB. Unfortunately, this approach results in filters with high input and output termination resistances, on the order of 12 k $\Omega$ .<sup>4</sup> In general, this type of high impedance is a major barrier to the use of MEMS filters in RF applications.

Separate efforts at the University of California at Berkeley and the University of Michigan investigated low-impedance MEMS filters using the radial bulk annular resonator (RBAR) concept (Fig. 3).<sup>5,6</sup> In concept, the approach can readily achieve impedance of less than 50  $\Omega$ , and the frequency of an RBAR filter has first-order independence of thickness. Both research groups worked with high-temperature processed polysilicon (poly-Si) as the resonator material. The material is difficult to handle during fabrication, and no low-impedance filters were fabricated successfully. In addition, although the RBAR approach can achieve very high  $Q$  (14,603 at 1.2 GHz), its single-resonator structure exhibits a narrow bandwidth

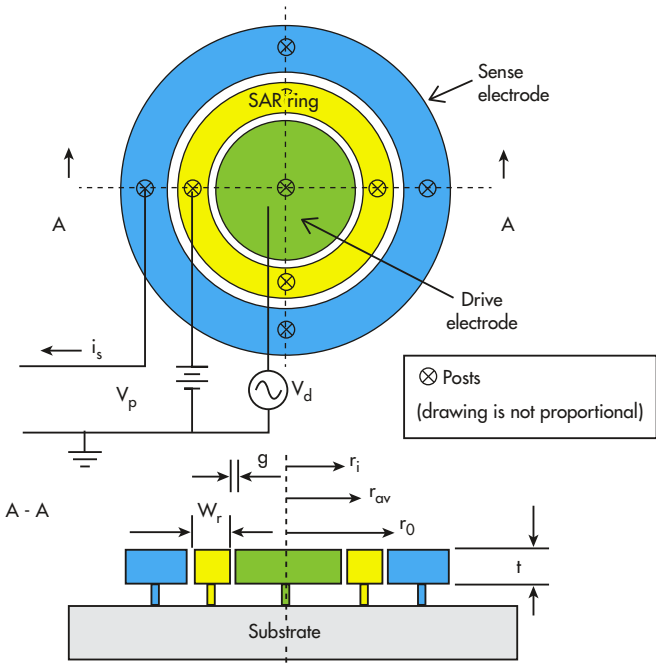
the authors on the mechanically coupled annual resonator (MCAR) concept. The main component of an MCAR design is a single annular resonator (SAR), which is similar to an RBAR (Fig. 4). It consists of a drive electrode, an SAR ring, and a sense electrode. Each is attached to the substrate by four posts.

The operating principle of a SAR is simple: electrical input signals are converted to mechanical energy, processed (with high  $Q$ ) in the mechanical domain, and then converted back to electrical signals at the output port for further processing by subsequent communications transceiver stages. For operation, a dc bias voltage,  $V_p$ , is applied to the SAR ring and an ac signal,  $V_d$ , is applied to the drive electrodes (Fig. 4). Voltage  $V_d$  generates an electrostatic force radially on the SAR ring at the ac input frequency. When the frequency of  $V_d$  matches one of the ring's resonant frequency modes, the ring starts to vibrate. An SAR can be modeled electrically as a parallel LCR circuit (Fig. 5).<sup>3,5,7,8</sup>

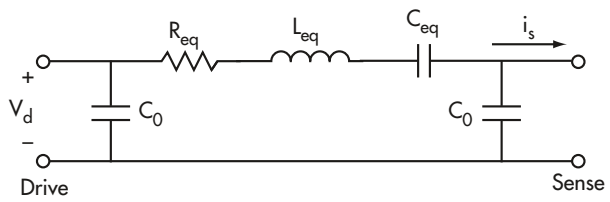
As reported in ref. 4, Eq. 1 is valid for  $r_{qv} \gg W_p$ , e.g.,  $r_{qv} > 2W_p$ :

$$f \approx (1/2W_p)(E/\rho)^{0.5} \quad (1)$$

where  $E$  is Young's modulus and  $\rho$  is the mass density of the SAR material. Equation 1 indicates that the resonant frequency is independent of thickness,  $t$ . Thus, a SAR's resonant frequency is insensitive to process variations in thickness. As a result, filters with different frequencies for multiband and RF channel-selection applications can be fabricated with one structural film deposition on one chip. This is a distinct advantage over most piezoelectric counterparts (e.g., FBAR and crystal filters), which require distinct material thickness to correspond to certain frequency. To build filters with multiband frequencies via the piezoelectric approach requires



4. This is the layout, cross-sectional view, and operating scheme for a single annular resonator (SAR).



5. This equivalent LCR circuit represents an electrostatic MEMS resonator.

several structural film depositions and patterning for different frequencies.<sup>5</sup>

For  $r_{qv} \gg W_p$ , the impedance,  $R_{eq}$ , is given by Eq. 2:

$$R_{eq} = [(E\rho)^{0.5}/Q\pi\epsilon_0^2] (g^4/2\pi r_{av}tV_p^2) \quad (2)$$

where  $Q$  is the quality factor,  $\epsilon_0$  is the permittivity of a vacuum,  $V_p$  is the resonator bias voltage,  $t$  is the thickness of the structural film, and  $g$  is the gap width of the drive and sense capacitors (Fig. 4). Equation 2 indicates that  $R_{eq}$  for an SAR is inversely proportional to the average radius and independent of  $W_p$ , and the insertion loss is independent of its resonant frequency.<sup>9</sup>

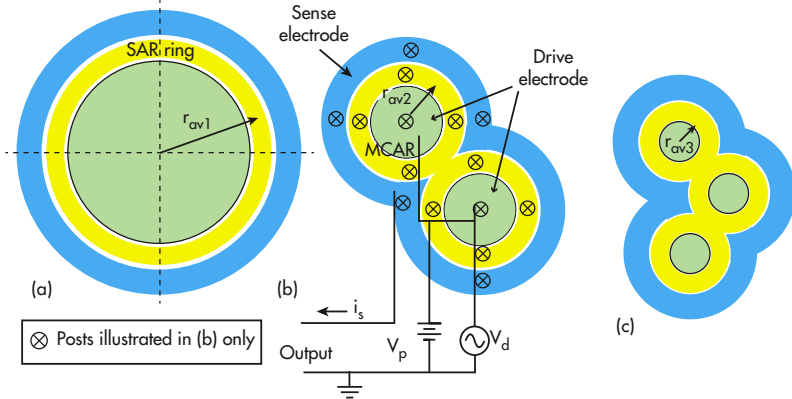
To save die area, several small SARs can be combined to

form an MCAR rather than fabricated one large SAR. A shown in Fig. 6,  $r_{av1}$  (a) =  $2r_{av2}$  (b) =  $3r_{av3}$  (c). Because the MCAR in b consists of 2 SARs, and the MCAR in (c consists of 3 SARs, both MCARs have the same capacitive area as the single SAR of a. Obviously, as the number of SARs in an MCAR increases, the area of the MCAR shrinks for the same capacitive area. It should be noted that this area shrinkage is not unlimited, because the frequency value from the Eq. 1 only valid when  $r_{av} > 2W_p$ . In other words, the inner radius of the SAR ring should be at least two times larger than the width of the SAR ring.

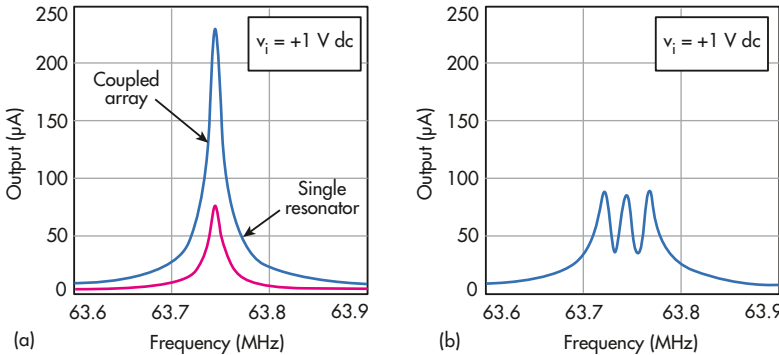
One method for lowering the impedance (motional resistance) of MEMS resonators is to combine currents from several resonators to produce a larger summed current. This can be done by connecting several resonators with identical frequency responses in parallel and driving them with the same input source,  $v_d$ . The total current through the resonator array for the same input voltage  $v_d$  is the individual resonator output current times the number of resonators in the array (Fig. 7a). The impedance is reduced by increasing the number of resonators.<sup>8-10</sup>

In reality, dimensional variations of resonators is unavoidable due to process variation, and these physical variations will cause variations in the frequencies of resonators even when they are on the same wafer. A small mismatch in the frequency of the resonators in an array (i.e., 0.01%) can dramatically impact the signal output (Fig. 7b). The high ripple is unacceptable for most communications applications.

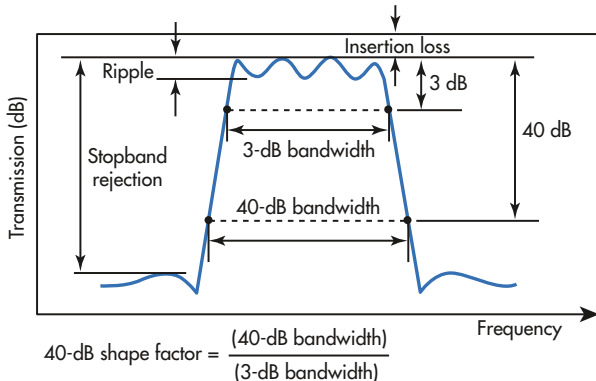
Mechanical coupling offers a superior solution to the mismatching problem. Multiple ( $n$ ) resonators can be coupled mechanically, such as the MCARs shown in Figs. 6b and c, to achieve a mechanical filter structure. Soft-spring-coupled resonators exhibit  $n$  modal frequencies, and each mode corresponds to a specific frequency and modal shape.<sup>7, 9, 11</sup> In contrast, stiff-coupled resonators automatically generate a single resonance response (i.e., mode) from all resonators, without the need for absolute matching of individual resonator responses.<sup>12</sup>



6. These layouts show (a) a SAR, (b) an MCAR consisting of two SARs, and (c) an MCAR consisting of three SARs.



7. Higher outputs can be achieved by electrically coupling three identical resonators (a), although even a 0.01% mismatch in resonator frequencies (b) can impact the output performance.



8. This is the passband and rejection band of an ideal bandpass filter.


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A stiff coupling structure may not increase the bandwidth, but many applications require only a small percent of the bandwidth. An industry-acceptable bandpass filter should have flat passband response, sharp rolloff, and high stopband rejection (Fig. 8). To achieve these qualities, a “soft MCAR” concept was developed for bandpass filters. In a soft MCAR, the SAR rings are coupled by a one-quarter-wavelength coupling beam, which acts as a soft coupling spring. As shown

in Fig. 9, two adjacent SAR rings are connected with a beam which is about one-quarter wavelength in length. The quarter-wavelength coupling is a state-of-the-art technique used to expand the bandwidth.<sup>8</sup>

Under a quarter-wavelength condition, the coupling beam dimension should satisfy the condition of Eq. 3, and its stiffness will be determined by the beam dimensions (Eq. 4):

$$\sinh(\alpha)\cos(\alpha) + \cosh(\alpha)\sin(\alpha) = 0 \quad (3)$$

The relationship between the bandwidth (B) for a filter with center frequency  $f_0$  and various stiffnesses is shown by Eq. 4<sup>13</sup>:

$$B = (f_0/k_c)(k_s/k_r) \quad (4)$$

where  $k_c$  is a normalized coupling coefficient derived from a ratio of resonance and 3-dB cutoff frequencies in a lowpass prototype for the desired filter, and is listed in filter cookbooks.<sup>14</sup> The coupling beam stiffness is determined by the beam dimensions (Eq. 5):

$$K_s = [EI_s \alpha^3 (\sin \alpha + \sinh \alpha)] / \{L_s^3 [\cos \alpha (\cosh \alpha - 1)]\} \quad (5)$$

with

$$\alpha = L_s [\rho W_s h \omega^2 / (EI_s)]^{0.25}$$

and

$$I_s = W_s h^3 / 12$$

where  $W_s$  is the width of the beam;  $h$  is the thickness of the beam; and  $L_s$  is the length of the beam. Similarly, the resonator stiffness can be calculated from its dimensions.<sup>15</sup>

The quality factor  $Q$  can be calculated from Eq. 6<sup>8</sup>:

$$Q = 1/P_{BW} = k_c(k_s/k_r) \quad (6)$$

where  $P_{bw}$  is the percent bandwidth and  $Q$  is determined by the soft coupled structure. The resistance of the termination resistor  $R_t$  can be calculated from Eq. 7<sup>5</sup>:

$$R_t = R_f \{ [Q/(q_f Q_{ftr})] - 1 \} \quad (7)$$

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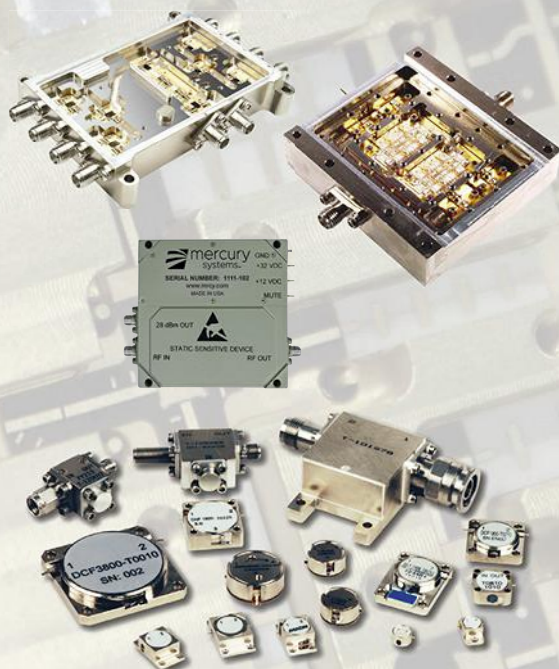
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## Low-Impedance MEMS Bandpass Filters

where  $Q$  is the unloaded quality factor of the constituent resonators;  $Q_{\text{filter}} = f_0/B$ ;  $R_i$  is the series motional resistance [which can be obtained from the actual filters using a vector network analyzer (VNA)]; and  $q_t$  is a normalized parameter that can be obtained from a filter cookbook.<sup>14</sup>

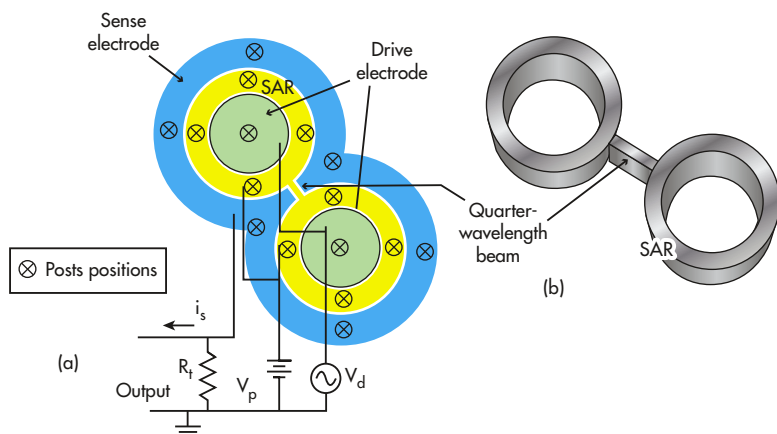
From Eq. 6, the ratio of  $k_r/k_s$  is another factor that provides sufficient percentage of bandwidth ( $P_{\text{BW}}$ ). Parameter  $k_c$  is a normalized coupling coefficient derived from a ratio of

resonance and 3-dB cutoff frequencies in a lowpass prototype for the desired filter, and is listed in filter cookbooks.<sup>14</sup> For a filter with 0.5-dB ripple,  $k_c$  is 0.72.<sup>14</sup> Parameter  $k_r$  is a dynamic resonator stiffness factor and is a function of locations along resonator length between two restraining anchor posts, as shown in Eq. 8<sup>8</sup>:

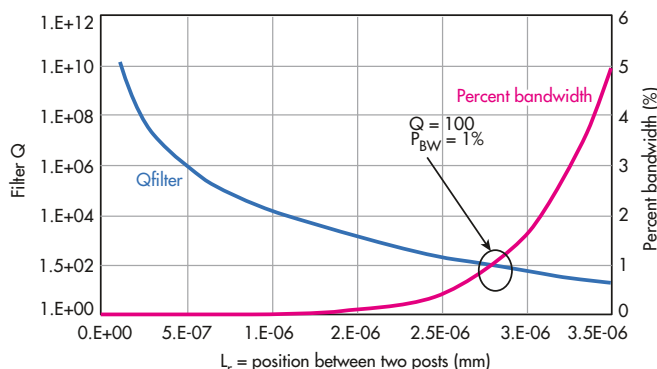
$$k_r = [(Ew_r h^3)/4][1/(L_r^3) + 1/(L_{r0} - L_r)^3] \quad (8)$$

where  $E$ ,  $w$ , and  $h$  are Young's modulus, the width of the resonator, and the height of the resonator, respectively. Parameter  $L_{r0}$  is the partial circumference (e.g., the length between two adjacent posts) of the resonator ring.

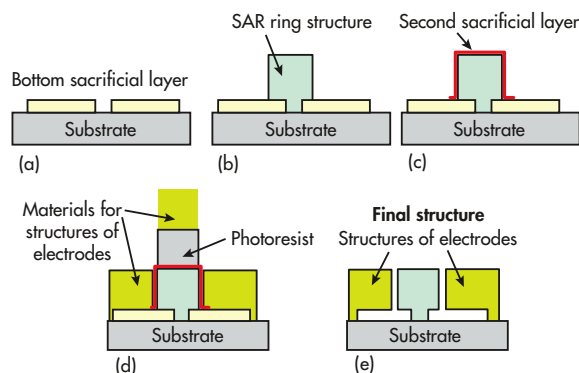
According to the process constraints of the fabrication facilities, the coupling beam dimensions were  $L_s = 1 \mu\text{m}$ ,  $W_s = 1 \mu\text{m}$ , and  $h = 2 \mu\text{m}$ . In this case, the quarter-wavelength conditions (Eqs. 3 and 4) were satisfied, with a  $k_r/k_s$  ratio of  $7 \times 10^{-7}$ . The  $Q_{\text{filter}}$  and  $P_{\text{BW}}$  versus coupling position were simulated (Fig. 10). The coupling beam was placed very close to the anchoring post at  $L_r = 2$  to  $3 \mu\text{m}$ , with  $P_{\text{BW}} = 1\%$  and  $Q = 100$ .



9. The layout of a soft MCAR (a) is compared to the three-dimensional (3D) view (b).



10. This simulated plot of filter  $Q$ ,  $Q_{\text{filter}}$ , also includes percent bandwidth versus coupling position with a  $k_r/k_s$  ratio of  $7 \times 10^{-7}$ .



11. The images show the process flow used in the fabrication of the MEMS bandpass filters.



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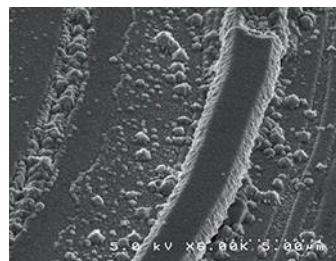
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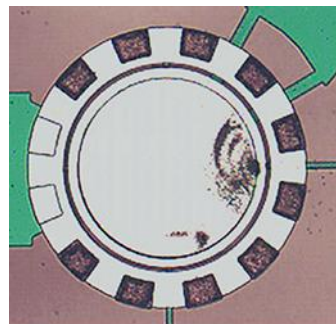
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Aluminum was selected as the ring and electrode material for the SAR, and Si wafers covered with oxide were used as substrates. Figure 11 shows the process flow. Two sacrifice layers of different materials were used in the process as shown in Figs. 11a and c. Figure 12 shows a scanning electron microscope (SEM) shot of the processed resonator ring.

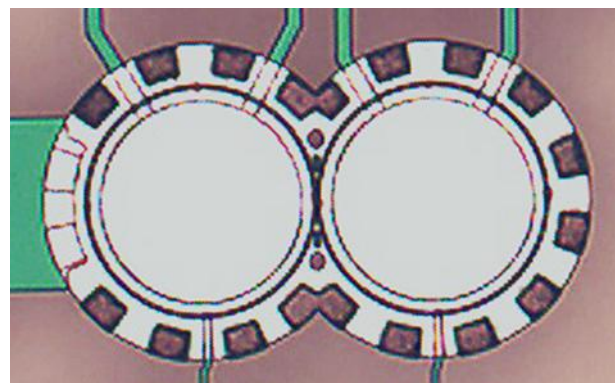
Images of the final fabricated SAR and soft MCAR filters are shown in Figs. 13 and 14, respectively. A commercial vector network analyzer (VNA), a model ZVB 20 from Rohde & Schwarz ([www.rohde-schwarz.com](http://www.rohde-schwarz.com)) with frequency range of 10 MHz to 20 GHz and a DC power supply, a model E3630A from Agilent, now Keysight Technologies ([www.keysight.com](http://www.keysight.com)), were used for RF testing (Fig. 15). A probe station was used for the on-wafer RF measurements. A customized setup was used to maintain the resonator under low vacuum conditions during measurements. A rubber tube connecting the mechanical vacuum pump at 6 mTorr was manually positioned at the resonator location to provide the vacuum environment.



12. This SEM image shows that the width of the resonator ring was about 3  $\mu\text{m}$ .

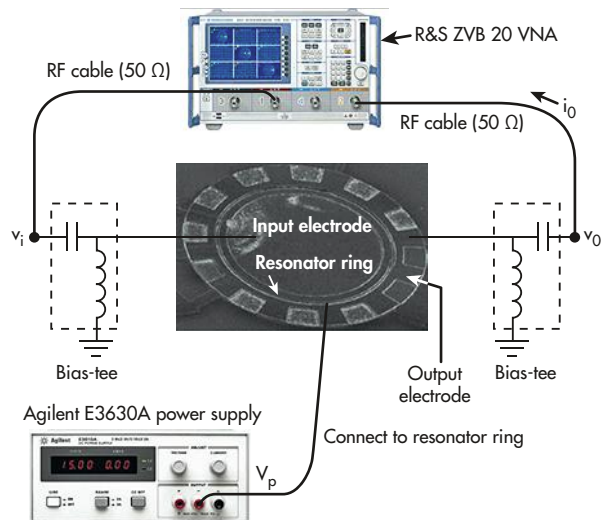


13. This is an image of a fabricated SAR filter.



14. This is an image of a fabricated soft MCAR filter.

The current research work has focused on demonstrating SAR and MCAR concepts. To simplify the design, processing, and testing of the experimental devices, not all circuit design rules were followed, such as the proper ground-signal-ground (GSG) wire coupling layout. Large wire



15. The two-port test setup including a high-performance microwave VNA.

dimensions and pads (about 3 mm) were used for ease of testing, with some signal loss as a result. When the experimental devices were tested without DC bias, even for devices with only the wire layout (the first layer of the structure), a broad peak of  $S_{21}$  (the through signal) around 1 GHz was observed, indicating signal loss through radiation from wires. To eliminate the effects of radiation loss, the  $S_{21}$  signal value of the resonator ring was deducted from the signal value when it was at a bias of 0 V dc. When it was at a bias of 10 V dc, the resonant frequencies of the SAR and soft MCAR were observed (see Figs. 16-18).

As demonstrated by the SEM of Fig. 12, the resonator width was 3  $\mu\text{m}$ , corresponding to a resonant frequency of 850 MHz according to Eq. 1. Measurement results matched the simulated values. Figure 16 shows measurement results of a SAR resonator, which exhibited a resonant frequency of ~850 MHz. The peak signal at 850 MHz was only 0.3 dB above the background noise, indicating that RF circuit design and the MEMS process need to be improved.

Measurement results for the soft MCAR also agreed with design simulations on the soft coupling ring. Figure 17 shows the measurement results for a soft MCAR with 3  $\mu\text{m}$  ring width. Again, it demonstrated a resonant frequency of 850 MHz, but with a wider bandwidth of 84 MHz (10% of center passband frequency). The reason for the wider bandwidth was due to the insufficient vacuum environment of the resonator during measurement ( $>10$  mTorr), as it is well known higher vacuum ( $<10^{-7}$  Torr) offers narrower bandwidth for resonators.<sup>2</sup>

Measurements on a resonator with 1- $\mu\text{m}$  width provide additional support for the MEMS filter design concept. The soft MCAR has a resonant frequency of 2.4 GHz with bandwidth of ~150 MHz (Fig. 18). The resonant frequency data also agrees with the calculation results from Eq. 1.

The bandwidth is larger than expected. However, this problem can be resolved by applying sufficiently high vacuum through a better experimental setup—e.g., using a turbopump instead of a mechanical pump alone. In real device applications, high vacuum for the resonator will be achieved by proper packaging and hermitically sealing, as widely used by mature technologies employed by shock sensor applications.

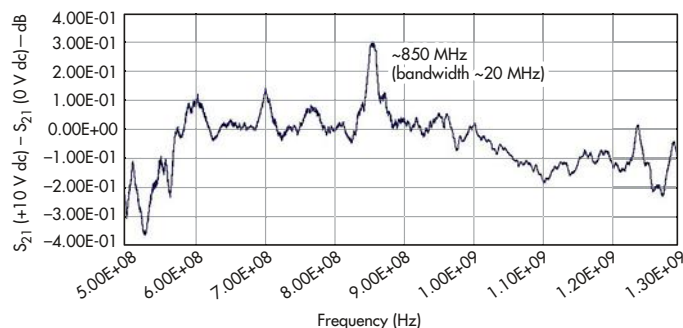
The impedance of a device under test (DUT) can be calculated using Eq. 9:

$$S_{11} = (Z_{in} - Z_0)/(Z_{in} + Z_0) \quad (9)$$

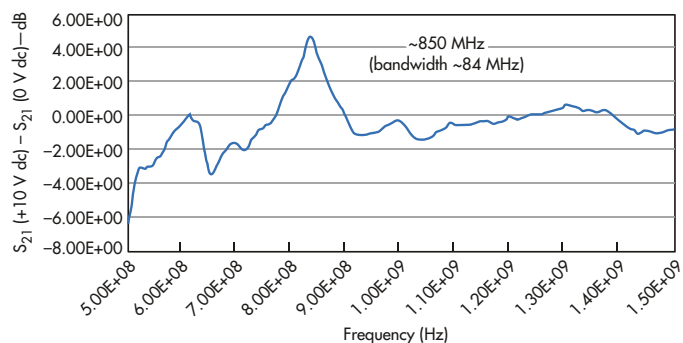
where  $Z_{in}$  equals  $50 \, \Omega$  (since measurements were normalized at  $50 \, \Omega$ ) and  $Z_0$  was the impedance of a resonator under test.

RF signal loss was observed at bare wires and pads of fabricated devices. Thus, it was difficult to measure the impedance of the fabricated resonators directly. Instead, impedances of resonators before and after 10-V dc activation were calculated from the corresponding  $S_{21}$  VNA data. It was then assumed that the activated device was in parallel with the radiation part of the resonator when it was at 0 V dc. The calculated results indicated that the impedances were close to the values provided by Eq. 2, as shown in the table. An impedance of  $1,480 \, \Omega$  was reached—much lower than other MEMS concepts.

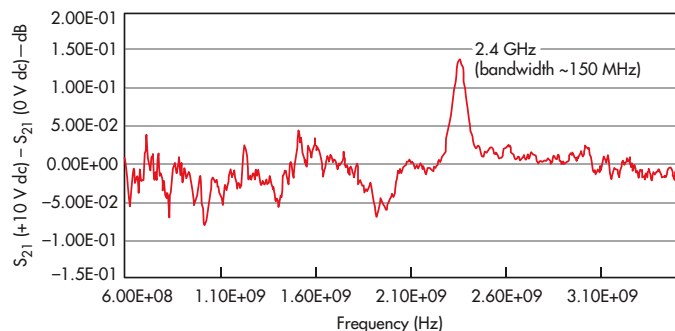
The measurement results demonstrated that the concepts were sound. The fabricated SARs and soft MCARs exhibited center bandpass frequencies at 850 MHz and 2.4 GHz, agreeing with design models. Soft MCAR filters showed wider bandwidth than SAR filters. Although the bandwidth is larger than expected, the issue can be resolved by improving the experimental setup to provide a better vacuum testing environment. The impedance results were also promising at  $<1.5 \, \text{k}\Omega$  with an activation voltage of 10 V dc. The researchers are confident in being to achieve an impedance of  $50 \, \Omega$  by rigidly controlling the fabrication process. **tmw**



16. The RF filter response was plotted for an SAR filter versus frequency at 10 V dc activation voltage (resonator width of  $3 \, \mu\text{m}$ ).



17. RF filter response was plotted for a soft MCAR filter versus frequency at 10 V dc activation voltage (resonator width of  $3 \, \mu\text{m}$ ).



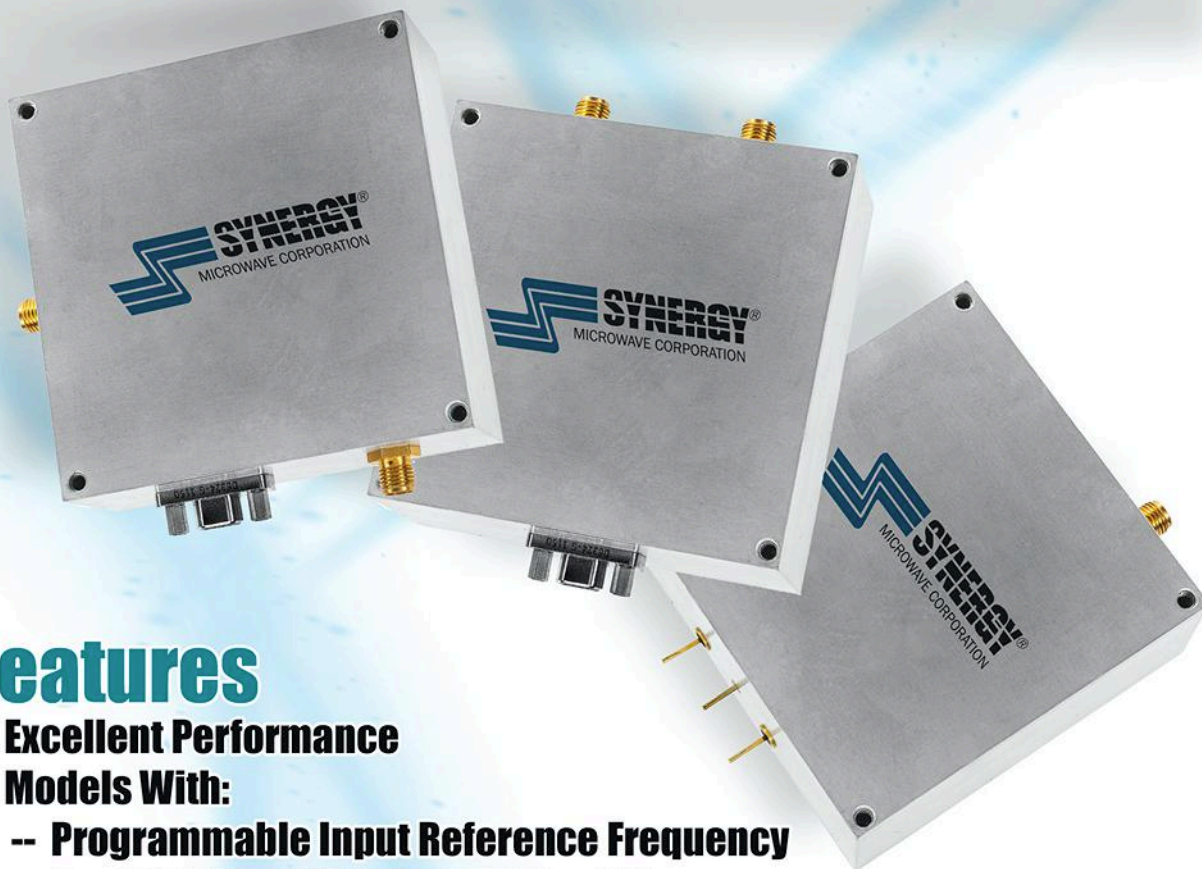
18. The RF filter response was plotted for a soft MCAR filter versus frequency at 10 V dc activation voltage (resonator width of  $1 \, \mu\text{m}$ ).

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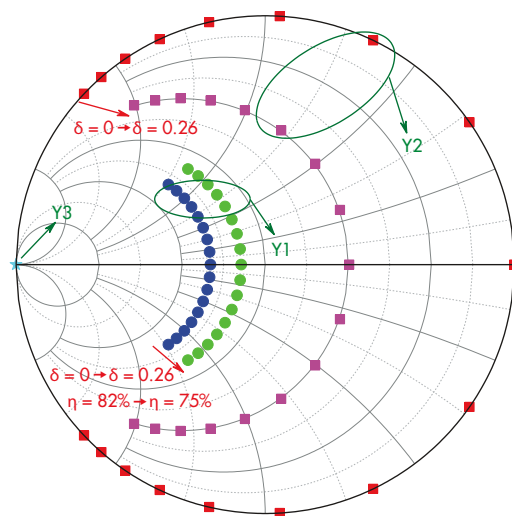
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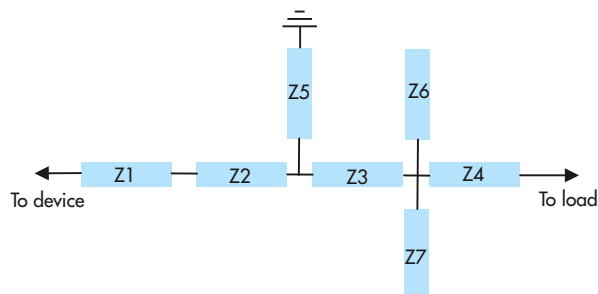
Efficiency is one of the most sought-after parameters in RF power amplifier (PA) design, since it translates directly to power consumption and operating cost. In continuous inverse Class F (CCF $^{-1}$ ) PAs, the current waveform factor,  $\delta$ , plays a major role in achieving high drain efficiency. With a modified low-pass output matching network (OMN), it is possible to constrain  $\delta$  to a limited range high drain efficiency even when operating a PA with broadband frequency coverage. The approach was demonstrated in an easy-to-implement PA design that operates from 1.0 to 1.9 GHz (a fractional bandwidth of 62%) that achieves +39.8 to +42.0 dBm output power across the frequency band with drain efficiency of 75.8 to 84.5% (average drain efficiency of 80%).

High-efficiency PAs are important components in modern communications systems, particularly when broadband frequency coverage and high-data-rate performance are required.<sup>1</sup> Classic harmonic tuned PAs, such as Class E amplifiers or those operating in Class F mode<sup>2</sup> or inverted Class F ( $F^{-1}$ ) mode typically operate with high efficiency but limited bandwidths. To extend the bandwidth of high-efficiency amplifiers, a continuous working mode was proposed by Steve Cripps in 2009, with additional concepts introduced more recently, including Class B/F mode,<sup>3</sup> continuous Class F mode,<sup>4</sup> and continuous Class  $F^{-1}$  mode.<sup>5</sup>

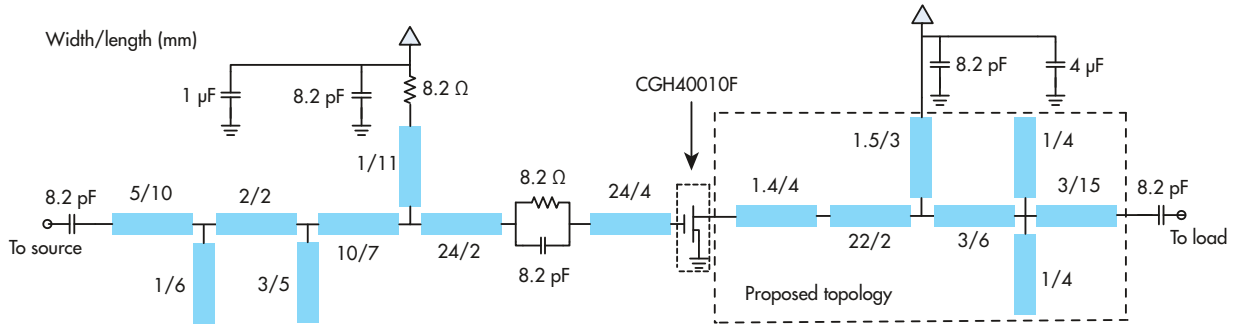
These continuous working modes require that second-harmonic loads are tuned to the edge of the Smith chart, which is an almost impossible condition to meet across a broad frequency range. The extended continuous class  $F^{-1}$  mode<sup>6</sup> is derived through managing the current waveform of classic continuous Class  $F^{-1}$  mode by adding a cosine term with a



1. The Smith chart shows the optimal admittance values required for designing matching networks for a PA for extended CCF-1 modes.



2. The OMN for a broadband CCF-1 mode PA consists of a simple, multiple microstrip-transmission-line structure.



3. This schematic diagram lists the dimensional requirements of the matching circuitry for the CCF-1 mode PA.

current waveform factor,  $\delta$ . Waveform factor  $\delta$  introduces a resistive part to the second-harmonic admittance, easing the requirements for strict impedance loads and, in the process, resulting in a more flexible design space.

Current waveform factor  $\delta$  plays a critical role in the efficiency of extended CCF<sup>-1</sup> mode PAs. The key point of designing an extended CCF<sup>-1</sup> mode PA is to design an output matching network (OMN) which allows the use of  $\delta$  constrained to a small range within the operating frequency band. Simulations with commercial computer-aided-engineering (CAE) software indicate that if the proposed OMN allows  $\delta$  to be maintained within a range of  $0 < \delta < 0.26$  across an operating frequency range of 1.0 to 1.9 GHz, the corresponding drain efficiency will be higher than 75%. This proposed OMN is relatively simple and easy to assemble.

### DESIGNING AN AMPLIFIER

The extended CCF<sup>-1</sup> PA can be derived by managing the current waveform of classical CCF<sup>-1</sup> PAs. It has a half-wave rectified sinusoidal voltage waveform at its intrinsic current-generator (I-gen) plane similar to CCF<sup>-1</sup> modes, while its current waveform represents a new family of current waveforms with waveform factor  $\delta$  varying between 0 and 1. The drain-source current ( $i_{ds}$ ) and voltage ( $V_{ds}$ ) waveform expressions are as follows:

$$i_{ds}(\theta) = (0.37 - 0.43\cos\theta + 0.06\cos3\theta)(1 - \gamma\sin\theta)(1 + \delta\cos\theta) \quad (1)$$

where  $-1 \leq \gamma \leq 1$

and

$$V_{ds}(\theta) = 1 + [2/(2)^{0.5}](\cos\theta) + 0.5\cos2\theta \quad (2)$$

Building upon these expressions, the output fundamental and harmonic admittances for the extended CCF<sup>-1</sup> mode can be found by means of Eqs. 3, 4, and 5, where  $G_{opt}$  represents the optimal admittance for the PAs transistors:

$$Y_{1f} = (2)^{0.5}[(1.16 - \delta) - j(0.33\delta\gamma - \gamma)(G_{opt})] \quad (3)$$

$$Y_{2f} = -2[-\delta + j(1.32 - \delta)\gamma]G_{opt} \quad (4)$$

$$Y_{3f} = \infty \quad (5)$$

Figure 1 depicts the fundamental, second, and third harmonic admittances of the extended CCF<sup>-1</sup> modes. As can be seen from the Smith chart,  $\delta = 0$  corresponds to the classical CCF<sup>-1</sup> mode. The fundamental load is on the constant susceptance circle, the second-harmonic load varies on the edge of the Smith chart, and the third-harmonic load is fixed at the short-circuit condition. Satisfying all three harmonic load conditions in a broadband PA design is difficult, usually leading to degraded performance in terms of efficiency and output power.

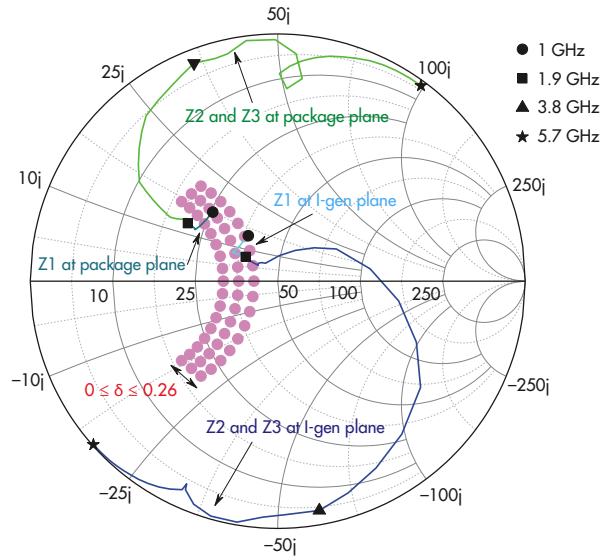
The extended CCF<sup>-1</sup> mode occurs when  $0 < \delta < 1$ . With variations of current waveform factor  $\delta$ , the optimal fundamental and second-harmonic loads are moving in opposite directions on the Smith chart. The second-harmonic load is located inside the Smith chart, which represents a resistive part to the second-harmonic admittance. This resistive part extends the design space with a slight sacrifice in efficiency and output power.

The drain efficiency of the extended CCF<sup>-1</sup> mode,  $\eta_D$ , can be calculated using Eq. 6:

$$\eta_D = [(2)0.5(1.16 - \delta)]/(2 - 1.16\delta) \quad (6)$$

As Eq. 6 shows,  $\eta_D$  is a function of the current waveform factor  $\delta$ . For a given predetermined minimum targeted efficiency  $\eta_D$ , the corresponding waveform factor  $\delta$  and impedance space on the Smith chart can be easily calculated. For an enlarged impedance space and range of  $\delta$ , a specific matching network must be designed. Equation 6 shows that  $\eta_D$  higher than 75% can be achieved when  $0 < \delta < 0.26$ , while  $\eta_D$  higher than 70% corresponds to  $0 < \delta < 0.4$ .

Figure 2 shows a proposed OMN topology based on multiple-section microstrip transmission lines. The serial transmission lines ( $Z_1, Z_2, Z_3$ , and  $Z_4$ ) act as inductances, while the shunt transmission lines ( $Z_5, Z_6$ , and  $Z_7$ ) act as capacitances. The combination of serial inductances and shunt capacitances form a five-stage lowpass filter network, which can provide optimal higher-order harmonic suppression. The use of symmetrical shunt open-circuit stubs ( $Z_6$  and  $Z_7$ ) helps achieve better broadband performance.

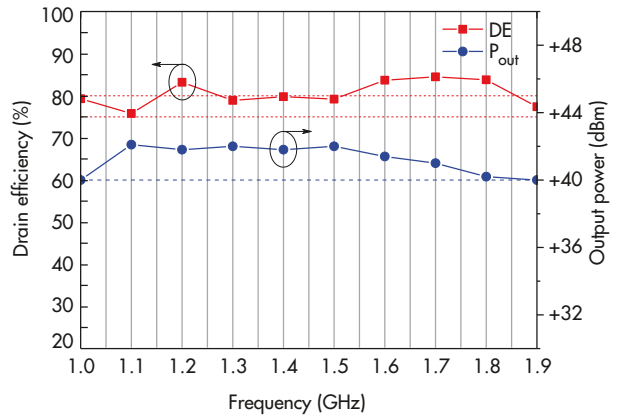


4. These are the impedance trajectories of the proposed OMN topology.

This proposed OMN circuitry can allow fundamental and harmonic loads varying more slowly over frequency on the Smith chart, which is beneficial for constraining current waveform factor  $\delta$  within smaller range in broadband applications. The modified OMN is suitable for the design of extended CCF<sup>-1</sup> mode PAs, and it is simple and easy to implement. Figure 3 shows a complete schematic diagram of the OMN circuitry with dimensions for the transmission lines.

Figure 4 presents the simulated fundamental and harmonic impedance trajectories of the proposed OMN over frequency at both the package plane and the I-gen plane. As can be seen, the fundamental impedance load is located inside the region of  $0 < \delta < 0.26$  as expected, while the second- and third-harmonic loads are located around the optimal region. Indeed, it is important to highlight that when the fundamental load is matched, the mismatching of the second- and third-harmonic loads causes only minimal degradation in efficiency and output power according to a load-pull simulation.<sup>7</sup> From the previous theoretical analysis, the drain efficiency  $\eta_D$  of this design has been calculated as exceeding 75% from 1.0 to 1.9 GHz.

To validate this design approach for the high-efficiency OMN, a broadband PA was designed and assembled based on a model CGH40010F GaN high-electron-mobility-transistor (HEMT) from Cree/Wolfspeed. The transistor is designed to provide as much as 10 W output power from a +28-V dc supply, from DC to 6 GHz. It is available in screw-down flange and solder-down pill-type packages. For the PA printed-circuit-board (PCB) material, rf-35 from Taconic was selected, with board thickness of 30 mil, copper thickness of 35  $\mu\text{m}$ , and relative dielectric constant,  $\epsilon_r$ , of 3.5 in the z axis (thickness) of the material.



5. Measurements were made from 1.0 to 1.9 GHz on the prototype continuous inverted Class F amplifier.

The prototype PA was tested with a gate bias of  $-2.7$  V dc and drain bias set at 28V dc, yielding a quiescent current of 68 mA. The test signal input power to the PA was fixed at +28 dBm. Figure 5 presents the results of the measurements. The PA's drain efficiency ranged from 75.8% to 84.5% while the output power ranged from +39.8 to +42.0 dBm across an operating frequency range of 1.0 to 1.9 GHz (a fractional bandwidth of 62%). **IMW**

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# Making the Case for Signal and Spectrum Analyzers

**What scenarios make an RF/microwave signal analyzer a better choice for a particular measurement than a traditional spectrum analyzer?**

**S**pectrum measurements are invaluable in the laboratory to evaluate the signal characteristics of a new design, and in the field to monitor known signals and search for interference. To make such measurements, engineers have typically turned to the RF/microwave spectrum analyzer. It is widely available in benchtop and portable varieties, and even in compact-module form with a USB interface that can add a PC's functionality and display screen to the instrument package.

However, instruments known as “signal analyzers” have also become available in recent years, with somewhat different capabilities and intended applications, including electromagnetic-compatibility (EMC) compliance testing and examining signals with complex modulation (*see “Measurements Help Minimize EMI and RFI,” p. 41*). The cost of these signal analyzers is higher than a traditional spectrum analyzer, so it helps to know when it makes sense to specify an RF/microwave signal analyzer rather than a spectrum analyzer.

## CONTRASTING STYLES

One obvious difference between a traditional spectrum analyzer and a modern signal analyzer is the type of information that must be learned about a signal of interest. A spectrum analyzer performs swept-frequency measurements across a preset portion of frequency spectrum. It measures any signals that are present at the time of the sweep, and then displays the amplitudes of all detected signals as a function of frequency. This has long been an effective means of measuring and displaying frequency-domain signal characteristics over broad bandwidths.



**1. The cost-effective CXA series of signal analyzers can be used as general signal analyzers and serve as EMI measurement receivers, with a frequency range of 9 kHz to 26.5 GHz and displayed average noise level (DANL) of -163 dBm. (Courtesy of Keysight Technologies)**

However, as communications signals grow in complexity, there's greater demand for more advanced methods of measuring and analyzing the time-domain characteristics—in the manner of an oscilloscope—as well as the frequency-domain characteristics of the detected signals. Signal analyzers, which are currently available as alternative measurement tools to a traditional spectrum analyzer, offer those advanced capabilities and thus continue to gain in popularity.

For example, the vector signal analyzer (VSA) is capable of measuring the amplitude and phase of a signal of interest—not just as a function of frequency, but also as a function of time. As a result, changes in a signal's characteristics over time, such as modulation, can be characterized.

A traditional spectrum analyzer is still a powerful tool when searching for unknown signals or evaluating the signal activity in an area and particular portion of spectrum. It also plays a key role when developing coexistence plans for multiple wireless signal sources in the same area that are closely spaced in frequency. In contrast, when using a VSA, the signal responses are typically expected if not known, and a VSA is less used as a signal search instrument.

The simplest way to think of a spectrum analyzer is as a tuned receiver with a display. An operator adjusts the tuning controls to set the range of minimum to maximum frequencies, and the bandwidth of the filter that is swept across that frequency range is also adjusted. Narrower bandwidths help

to separate signals that are close together in frequency. The measurement results come as graphical depictions of signal amplitude versus frequency for a selected bandwidth.

As modern digitizers become more capable, they also assume a greater part of a spectrum analyzer's architecture, with high-speed analog-to-digital converters (ADCs) often used to digitize an analyzer's IF signals for further processing in the digital realm. Techniques such as fast Fourier transforms (FFTs) can be performed to develop displays of the digitized data and show different aspects of measured input signals. FFTs are the basis for real-time spectrum analyzers (RTAs), for example, which use FFTs in parallel to process a wide instantaneous bandwidth to better capture transient events.

Perhaps the simplest way to think of a signal analyzer is that it may start with a spectrum analyzer, but it adds functionality to tackle more complicated measurements, such as the measurement of phase/time possible with a VSA. Signal analyzers typically provide extensive demodulation capabilities to analyze signals with complex, digital modulation.

### COMBINATION INSTRUMENTS

Many modern signal analyzers are actually combinations of several instruments, such as spectrum analyzers and VSAs. They may also include real-time analyzers (RTAs), which allow measurements of signals according to precise time references. Consequently, the synchronization and timing of signals can be studied in addition to frequency, amplitude, and phase.

As an example, the CXA series of signal analyzers from Keysight Technologies (Fig. 1) can act as spectrum analyzers, but they also perform EMI measurements with a frequency range of 9 kHz to 26.5 GHz and displayed average noise level (DANL) of -163 dBm. These analyzers will also work with VSA software to perform measurements of phase and complex modulation, and can be fitted with a tracking generator for scalar-network-analyzer (SNA) measurements to 6 GHz.

The R&S FSW signal and spectrum analyzer (Fig. 2) from Rohde & Schwarz ([www.rohde-schwarz.com](http://www.rohde-schwarz.com)) is a combination signal and spectrum analyzer, available with a range of instantaneous measurement bandwidths across a measurement frequency range as wide as 2 Hz to 85 GHz. It can be equipped with analysis bandwidths extending to 2 GHz for wideband modulation and pulse measurements, and features real-time analysis across bandwidths as wide as 512 MHz. Whether considered a spectrum or a signal analyzer, this instrument offers exceptional performance, with phase noise of -137 dBc/Hz offset 10 kHz from a 1-GHz carrier.

Another example of a multi-function instrument is the MDO4000 Series of oscilloscopes from Tektronix, which combines time-domain and frequency-domain analysis in the same instrument (Fig. 3). Though primarily an oscilloscope options add other instrument functions that include a spectrum analyzer from 9 kHz to 3 GHz or 9 kHz to 6 GHz.

The MDO4000 is well-suited for EMI troubleshooting, with an oscilloscope portion that features four analog channels with bandwidths to 1 GHz and a 5-Gsample/s maximum sampling rate. In addition to a scope and spectrum analyzer, it can be equipped with four more measurement functions: logic analyzer, protocol analyzer, arbitrary waveform generator, and digital voltmeter.

Traditional spectrum analyzers as well as modern signal analyzers no longer automatically come with display screens. As test instruments are designed into modular formats such as PXI, or with USB ports for connection to a PC, they instead use the computer's display screens to show test results.

On that front, the RSA500A from Tektronix is a pocket-sized spectrum analyzer (Fig. 4) that connects to any USB computing device for control and display, greatly simplifying the task of making in-field measurements. In spite of the small size, it is a full-featured spectrum analyzer with frequency range of 9 kHz to either 3 GHz or 7.5 GHz, and acquisition bandwidth as wide as 40 MHz. By using a computer's screen and processing power, it packs the measurement capabilities of a benchtop spectrum analyzer that was once about 10 times its size. **mw**



**2. The R&S FSW is a combination signal and spectrum analyzer with a frequency range as wide as 2 Hz to 85 GHz.** (Courtesy of Rohde & Schwarz)



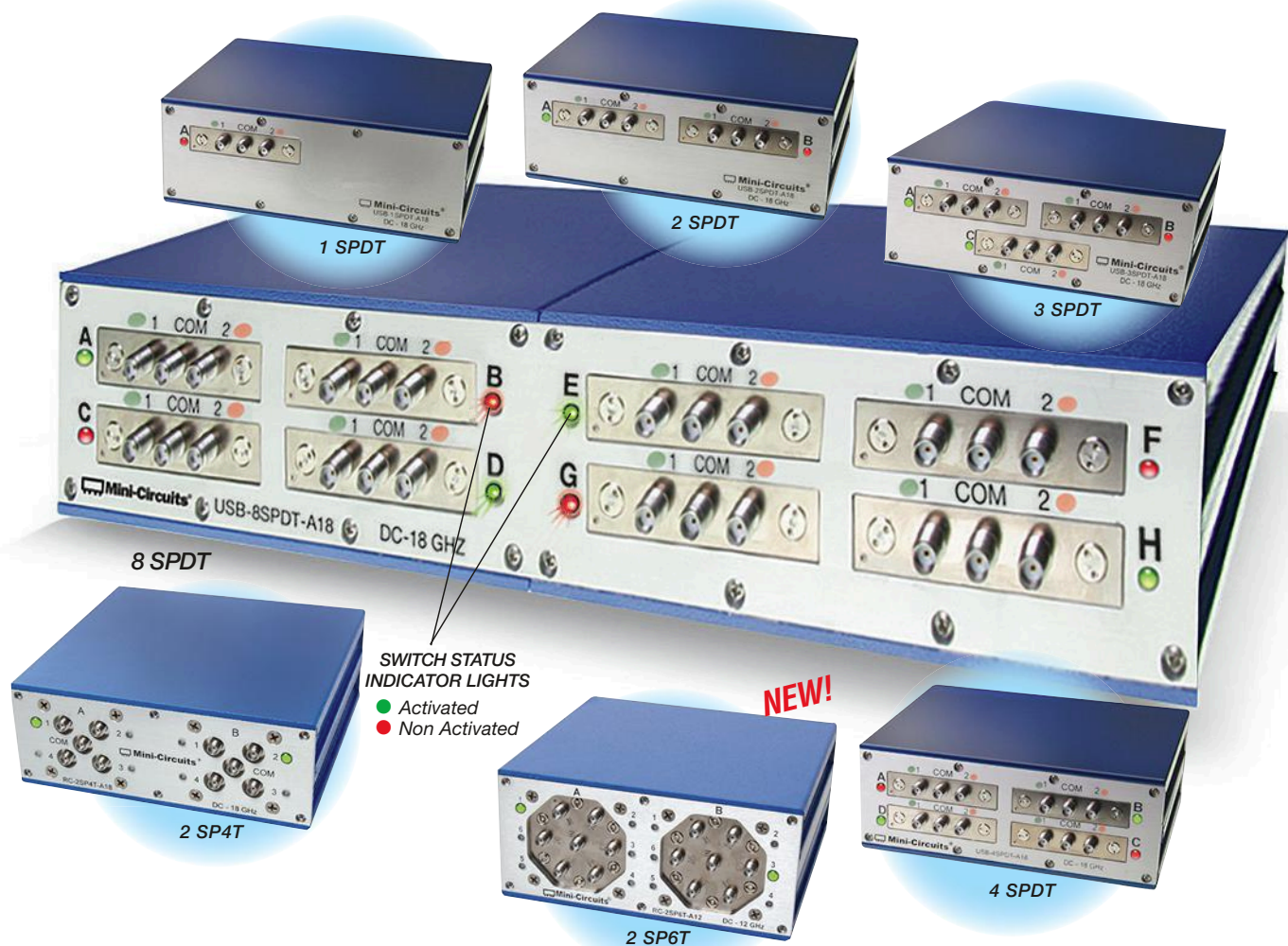
**3. The MDO4000 line of oscilloscopes can incorporate as many as six other measurement functions, including a spectrum analyzer from 9 kHz to 3 GHz or 9 kHz to 6 GHz.** (Courtesy of Tektronix Inc.)



**4. The RSA500A is a USB-powered and -controlled spectrum analyzer that uses a computer's processing power and display screen.** (Courtesy of Tektronix Inc.)

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## CALIBRATE YOUR WAY TO MEASUREMENT SUCCESS

**R**EGULARLY CALIBRATING INSTRUMENTS is necessary in order to reduce measurement errors. It is therefore important to understand how calibration reduces measurement risk, as well as knowing the capabilities of a calibration provider. In the application note, "Eliminate Risk with Proper Calibration," Keysight Technologies describes measurement risk and its contributing factors. The application note then explains calibration and how it mitigates risk. Different extents of calibration are described as well.

The application note defines measurement risk as the probability of making an incorrect decision. A measurement process has four possible outcomes: Correct pass, correct fail, false pass, and false fail. Measurement risk is directly related to measurement consistency, accuracy, and repeatability. A term used to calculate risk is

measurement uncertainty, which takes all the possible errors and combines them to produce a standard deviation. Statistics are then used to calculate risk.

Measurement errors can result from intrinsic, environmental, installation, or operational sources. Intrinsic errors are caused by limitations or inaccuracies of the measurement instrument, while environmental errors are due to the instrument surroundings. Installation errors are a result of connected accessories, such as cables, connectors, probes, and switch boxes. Lastly, operational errors are caused by the engineer or technician operating the equipment.

The application note explains that the intrinsic performance of instruments can change over time. Thus, the uncertainty surrounding performance increases. Increased measurement un-

certainty lowers the prospects of achieving consistent, accurate, and repeatable measurements. Proper calibration accurately measures test equipment performance. The document states that

the basic definition of calibration is the performance measurement of a test asset based on the international metrology standards.

Different calibration providers offer different coverage scopes. The number of tests and test points indicate the extensiveness of coverage. Providing actual data is essential, as it demonstrates the degree of testing performed. The application note then describes how measurement uncertainty can be determined by various methods. The guardbanding technique, which is used to reduce measurement risk, is mentioned. Lastly, the adjustment-performing capability of a calibration supplier is discussed.

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## "RE-CAFFEINATE" A RADAR SYSTEM DESIGN

**AN ARTICLE PUBLISHED** in 2012 described how to build a synthetic aperture radar using a laptop coffee-can radar system. A few years later, Dr. Jim Carroll and Dr. Gent Paparisto decided to redesign the radar system by taking advantage of the capabilities of the NI AWR Design Environment. In the application note, "OCW Coffee-Can Radar Optimized in NI AWR Software," National Instruments describes how the original coffee-can radar system was redesigned with better performance and lower cost. The NI AWR Design Environment was used to design the new system.

The original coffee-can radar system operated in the 2.4-GHz industrial, scientific, and medical (ISM) frequency band. That design used readily available connectorized components. The baseband information was extracted with a laptop sound card. MATLAB was utilized to perform the necessary processing.

The new "re-caffeinated" radar system design was achieved by taking advantage of the capabilities of the NI AWR design software. The new system design ultimately achieved improved performance in a reduced footprint while also lowering costs.

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awrcorp.com**

First, the original design was created in the Visual System Simulator (VSS) software. Next, a redesigned system was also created in VSS. While this new system essentially had the same topology as the original, surface-mount parts were used in place of the original ones. Furthermore, the original coffee-can antennas were replaced with Vivaldi antennas.

The application note presents the VSS system-level analysis of both the original and new designs. The new design demonstrated that it could transmit greater output power than the original, due much in part to a better performing power amplifier (PA). In addition, the intermediate-frequency (IF) power spectrum is shown for both designs. These simulations were performed with a frequency-modulated-continuous-wave (FMCW) signal propagating through the respective systems. Time-domain simulations of target distance and velocity are presented as well.

The radar system was built on a 62-mil-thick FR4 board. The application note also describes the Vivaldi antennas, which replaced the original coffee-can antennas. Finally, a photo of the complete system is shown.



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# Transceiver IC Eases Transition from 4G to 5G

This highly integrated radio solution contains a DPD engine for power amplifier linearization along with multiple wideband transmitters and receivers.

**EXPECTATIONS ARE HIGH** for Fifth-Generation (5G) cellular wireless networks, even though they are still several years in the making. Until then, 3G and 4G networks are and will be in service, requiring RF hardware that can provide reliable 3G and 4G performance while enabling a transition to the performance levels needed for 5G systems.

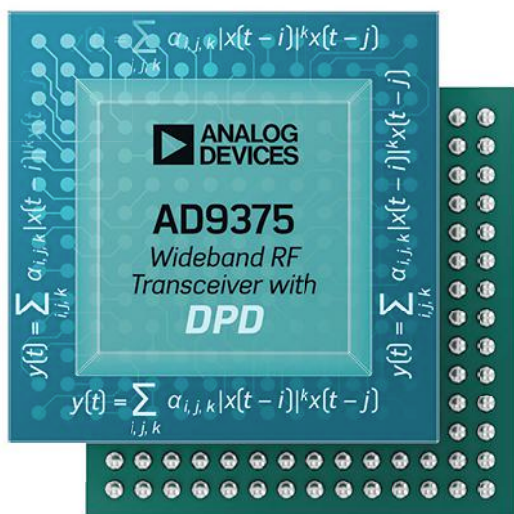
The latest member of the RadioVerse family of highly integrated transceivers from Analog Devices ([www.analog.com](http://www.analog.com)), the AD9375, provides the performance and flexibility to make the transition, stacked as it is with a fully integrated digital predistortion (DPD) solution, multiple receivers and transmitters, on-board frequency synthesizers, and a broad RF range from 300 MHz to 6 GHz for signals from a number of different wireless standards. In spite of the extensive functionality, it is

a low-power-consumption device (5 W) well suited for use in small wireless base transceiver stations (BTS) where power and size must be conserved, such as those employing large numbers of antennas in massive multiple-input, multiple-output (MIMO) configurations.

Radio designers are facing some severe challenges for 4G wireless networks, let alone for eventually emerging 5G networks. As the numbers of wireless users, both people and things, continue to grow at such a rapid pace worldwide, BTSs and small cells must provide high performance with the flexibility to meet dynamic operating conditions and requirements. Users will be people expecting everything they can get from a smart cellphone, and probably an even greater number of things, in the form of Internet of Things (IoT) sensors and other IoT devices.

Seamless wireless coverage and service for this growing number of users will be made possible by more BTSs and an increasing number of small cells; in particular, the small cells help to prevent gaps in the wireless coverage such as in large office buildings. The AD9375 is an excellent starting point for these small cells because of its low power consumption, multiple receivers and transmitters, and flexible software-defined-radio (SDR) architecture. Since 5G standards are being formulated in terms of center frequencies, bandwidths, and modulation schemes, the AD9375 provides the coverage and programmability to tune where it is needed when those standards come, while still meeting current 4G requirements.

The AD9375 (Fig. 1) includes an impressive number of transmit and receive functions in a single 12 × 12 mm BGA packaged device with a tunable frequency range of 300 MHz to 6 GHz. Fabricated with a 65-nm silicon CMOS semiconductor process, it contains dual differential transmitters, dual differential receivers, an observation receiver with two inputs, a sniffer receiver with three inputs and, most importantly, the on-chip capability to linearize a connected high-power transmit amplifier with a digital-predistortion (DPD) algo-



1. The AD9375 RadioVerse transceiver contains a fully integrated DPD solution, two differential transmitters, two differential receivers, an observation receiver, and a sniffer receiver with total frequency range of 300 MHz to 6 GHz in a compact BGA package.

rithm. The AD9375 integrates a low-power DPD actuator and adaption engine for improving the linearity of a connected transmit power amplifier (PA), so that transmit linearity can be achieved without the power consumption normally associated with such functionality.

The AD9375 transceiver is similar to its predecessor, the AD9371, with two 100-MHz receivers, two 250-MHz transmitters, a two-input observation receiver, and a three-input sniffer receiver, with system-level interconnections via a 6-Gb/s JESD204B interface. In fact, the packaged devices are pin-for-pin compatible. The integrated DPD circuitry within the AD9375 provides transmit linearity without excessive power consumption, especially enticing for small cells. It features instantaneous bandwidth as wide as 40 MHz for 3G and 4G waveforms. Compared to off-chip DPD methods based on field-programmable gate arrays (FPGAs), the on-chip circuitry can effectively linearize a transmit PA with as much as a 90% reduction in power consumption. Performing the DPD functionality with on-chip circuitry also simplifies the system-level design of a BTS or small cell, cutting the number of JESD204B interface lanes in half and requiring less FPGA resources.

The AD9375 features fully integrated and independent fractional-N frequency synthesizers to generate the local oscillators (LOs) required for transmit, receive, observation receiver, and clock functions. The transmitters and receivers support frequency-division-duplex (FDD) and time-division-duplex (TDD) operation.

The AD9375's differential transmitters produce large-signal bandwidths as wide as 250 MHz from 300 MHz to 6 GHz. When used for a 3G system such as the Universal Mobile Telecommunications System (UMTS), the LOs offer signals at 700, 2600, 3500, and 5500 MHz with as much as +7 dBm output power at 700 and 2600 MHz, as much as +6 dBm output power at 3500 MHz, and as much as +4 dBm output power at 5500 MHz.

Across those wide transmit bandwidths, the typical amplitude flatness is  $\pm 0.5$  dB, with typical deviation from linear phase within 10 deg. The transmit power can be controlled over a range of 0 to 42 dB with power control resolution of typically 0.05 dB. In spite of the small size of the AD9375, the different transmitters are well isolated, from each other and from the receivers. The transmitter-to-transmitter isolation ranges from 65 dB or better for the 700-, 2600-, and 3500-MHz LOs to 50 dB for the 5500-MHz LO. The isolation between the two main receivers and between either of the receivers and any of the transmitters is typically 60 dB or better.

## RECEIVING THE FUTURE

The AD9375's receivers are also tunable from 300 MHz to 6 GHz, offering a gain range of 0 to 30 dB in 0.5-dB gain steps. The gain amplitude flatness is within  $\pm 0.5$  dB. The receive



**2. The AD9375 small cell radio reference design helps system designers working on 3G, 4G, and 5G small cells to come to market quickly with a low-power radio design characterized for LTE use.**

bandwidth can be set from 8 to 100 MHz. The maximum recommended input signal power to the receivers is -14 dBm at 0-dB attenuation. The receiver noise figure ranges from 12 dB with the 700-MHz LO to 18 dB with the 5500-MHz LO, while its input third-order intercept point (IIP3) performance is remarkably consistent with frequency, varying only from typically +22 dBm for operation with the 700-MHz LO to typically +20 dBm for operation with the 5500-MHz LO.

In addition, the AD9375 includes a two-input observation receiver and a three-input sniffer receiver. The observation receiver has a tunable center frequency range from 300 MHz to 6 GHz with gain range of 0 to 18 dB; maximum input levels shouldn't exceed -13 dBm. The typical amplitude ripple is  $\pm 0.5$  dB across a 250-MHz bandwidth. For the same receiver bandwidth, the deviation from linear phase is typically  $\pm 10$  deg. The sniffer receiver has two input ports with low-noise amplifiers (LNAs) for detecting signals across 20-MHz bandwidths from 300 to 4000 MHz.

The AD9375 transceiver is supplied in a 196-ball BGA—a small package with large benefits. However, it is not left to wireless system designers to extract those benefits. The AD9375 is supported by a large number of models and commercial modeling tools, including MATLAB and Simulink from MathWorks ([www.mathworks.com](http://www.mathworks.com)), to help speed the prototyping process. In addition, the transceiver is available as part of an evaluation kit and as a reference design. The reference design, developed in partnership with radio systems designer Benetel Ltd. ([www.benetel.com](http://www.benetel.com)), supports LTE with 20-MHz channels in a two-transmitter, two-receive system configuration with 250-mW output power per antenna. The reference design (Fig. 2) is a circuit measuring just 88 × 83 mm that consumes less than 10 W power. **mw**

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# Double-Balanced Mixer Converts Wideband Signals from 3 to 20 GHz

Now a part of Analog Devices, Linear Technology continues a strong track record of developing integrated RF/microwave components with outstanding performance.

**FREQUENCIES CAN BE** translated in many ways for signal processing, but frequency mixers tuned with local oscillators (LOs) may still be one of the most trusted methods for conversion, and the LTC5553 double-balanced mixer from Linear Technology (recently acquired by Analog Devices) offers one of the widest bandwidths of any mixer in one of the smallest packages. With an RF range of 3 to 20 GHz and on-board LO amplifier, the integrated-circuit (IC) mixer is supplied in a tiny surface-mount QFN package measuring just 3 x 2 mm. It can be used for frequency upconversion or downconversion, working with an LO frequency range of 1 to 20 GHz and an intermediate-frequency (IF) range of 0.5 to 9.0 GHz.

The LTC5553 (*see figure*) has integrated wideband baluns that result in RF, LO, and IF ports matched to 50  $\Omega$  and ready for interconnections in many application circuits. The integration of an LO amplifier eliminated the need for external amplifier and matching circuitry when connecting an LO source. The mixer delivers the wideband performance suitable for a wide range of applications, including 4G and 5G wireless access, point-to-point microwave radios, radar systems, satellite modems, and test equipment. With its fast times of turning on (typically 0.2  $\mu$ s) and off (typically 0.1  $\mu$ s), the double-balanced mixer is also a good fit for time-division-duplex (TDD) radio systems.

The integrated LO amplifier allows the use of typical LO power level of 0 dBm without compromise in conversion-loss performance. The conversion loss is low across the full bandwidth. For a downconversion application with IF of 1890 MHz, the conversion loss is typically 8.2 dB for an RF of 4 GHz, 9.0 dB for an RF of 10 GHz, 11.3 dB for an RF of 14



The LTC5553 double-balanced mixer provides an RF range of 3 to 20 GHz in a miniature plastic QFN package.

GHz, and 11.6 dB for an RF of 17 GHz. For an upconversion application with the same IF, the conversion loss is essentially the same, typically 8.3 dB for an RF of 4 GHz, 9.3 dB for an RF of 10 GHz, 11.9 dB for an RF of 14 GHz, and 11.5 dB for an RF of 17 GHz. For applications that must operate within a wide temperature range, the conversion loss remains fairly constant with temperature. When tested with an RF input of 9.8 GHz, the conversion loss as a function of temperature was 0.006 dB/ $^{\circ}$ C from -40 to +105 $^{\circ}$ C.

In spite of the small size, the mixer features well isolated ports, with typical RF-to-LO isolation of better than 40 dB and typical RF-to-IF isolation of better than 32 dB, with both characteristics specified across the full RF frequency range. The tiny mixer also keeps LO signals where they belong, with typical LO-to-RF leakage of -32 dBm at 17 GHz. On the high side of the dynamic range, the mixer achieves input third-order intercept point (IIP3) of +23.9 dBm at 14 GHz and +21.5 dBm at 17 GHz. The single-sideband (SSB) noise figure is typically 10.9 dB at 10 GHz and 12.8 dB at 15.7 GHz.

The broadband double-balanced mixer is housed in a 12-lead plastic QFN package with each port connection surrounded on either side by ground lead connections. It draws just 132 mA current from a +3.3 V dc supply and is rated for operating temperatures from -40 to +105 $^{\circ}$ C. Although it is designed to perform well with low LO power, it can handle LO levels as high as +10 dBm and RF and IF input power levels as high as +20 dBm. One mixer may not do everything, but this one does come close. **ITW**

ANALOG DEVICES Inc., 1630 McCarthy Blvd., Milpitas, CA 95035-7417; (408) 432-1900, [www.linear.com](http://www.linear.com).



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Hand Flex cables are available in 0.086" and 0.141" diameters, with a tight turn radius of 6 or 8 mm, respectively. Choose from SMA, SMA Right-Angle, SMA Bulkhead, SMP Right-Angle Snap-On and N-Type connectors to support a wide variety of system configurations.

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# LoRa+BLE Puts IoT Everywhere on the Map

Thanks to the blend of LoRa technology and Bluetooth Low Energy, the Internet of Things can reach locations without telecommunications infrastructure.

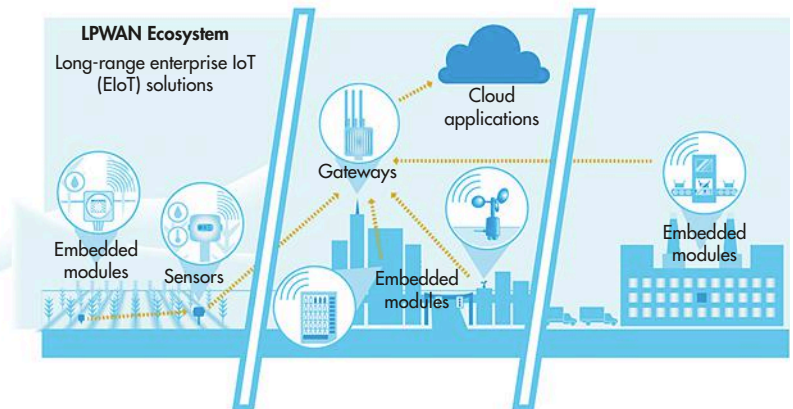
**“FAR-FLUNG” IS A** fun phrase, particularly for a Brit like me who enjoys American sayings that are colorful, baffling, and perfect all at the same time. It sounds like the kind of old-timey language you would hear in black-and-white newsreels from the early 1900s: “News flash. Dateline Chicago. Here we see a vehicle of the future, called an aero-plane, taking flight to far-flung destinations like Peoria and ‘Saint Louee’ in less than a day. What will they think of next? A phonograph you can fit in your watch pocket?”

When it comes to the Internet of Things (IoT), far-flung is also fun because it’s about where the future of IoT lies: Way out on the edge of where sensor device-to-cloud wireless connectivity has ever been able to go geographically.

IoT has been anything but far-flung up until now. Yes, it is already being deployed in lots of locations. The analyst reports that come out each month say that billions upon billions of wireless sensors and devices will be deployed in the next few years.

But if you fling a dart at a map, chances are you would hit a geographic location where IoT was once likely to be difficult or challenging to achieve—either technically or economically. That’s because the vast majority of wireless IoT deployments today are done within arm’s reach of telecommunications infrastructure, whether in the form of wired infrastructure or wireless towers.

However, there are just as many locations where that infrastructure is not present or is too costly to use for an IoT deployment. And guess what? Those areas of the map happen to be areas that have myriad uses for low-power, long-



This diagram represents a simple geographic setup of a long-range enterprise IoT scenario.

range IoT, whether for monitoring and information relay of remote industrial equipment, pipelines, energy tanks, soil, moisture, and more.

## INFRASTRUCTURE DEPENDENCY

There’s a good reason why IoT has stuck close to that infrastructure, which typically means close to cities and towns and the routes that connect them. IoT deployments rely on Ethernet, fiber, and cellular infrastructure as the conduit for data sent to and received from those wireless devices. That provides the backhaul for an engineer in Chicago to receive packets of data from a set of sensors in Peoria, and to send instructions and other information to the wireless IoT devices remotely.

Typically, that backhaul is provided via fiber through something like a Wi-Fi or cellular connection from a gateway. It acts as the go-between that connects the network of devices with fiber or wireless infrastructure for two-way communications

with the IoT deployment. But what happens when there isn't any fiber or cell tower in sight? Or when there is a cell signal, but the cost or power demands are just too prohibitive for the IoT deployment to make sense?

Well, in the past, nothing would happen. The IoT project would simply be shelved as impractical or never be proposed in the first place. Such a scenario has put an artificial boundary around IoT deployments to date. Lots of implementations are happening, but how many more implementations would be on the drawing board if those geographic boundaries disappeared and you could fling them as far as you hypothetically wanted them flung?

That is exactly what is possible when you combine a new technology, LoRa, with one that is already a fundamental element of so many IoT deployments: Bluetooth Low Energy (BLE).

IoT networks that utilize BLE (also known as Bluetooth Smart) can be deployed in nearly any physical space, given its small footprint and energy-miser architecture that enable small wireless sensors and controls to operate on a battery charge for years. With BLE, these small devices can be placed nearly anywhere within a given location, allowing users to put sensors and other devices in spots that are often physically impossible, technically difficult, or fiscally impractical for traditional wired devices. Simply put, BLE works for IoT, which is why engineers embrace it as the foundation for short-range wireless connectivity in these deployments.

But without backhaul, those BLE devices are simply talking to one another in an echo chamber—they lack two-way communication back to the people who want to get that data and send instructions. As a result, the majority of BLE-based IoT applications use the mobile phone as a gateway back to the cloud via its cellular connection. But in absence of a cellular or mobile phone, what do you do? This is where LoRa comes in.

## ENTER LoRa TECHNOLOGY

LoRa, often referred to as a low-power wide-area-network (LPWAN), provides secure, bidirectional data transfer and communications with IoT networks over long distances for years without a battery change. It can send and receive signals up to 10 miles, and that distance can extend to hundreds of miles with repeaters, if needed. LoRa works well as a complement for BLE in battery-powered networks of IoT devices because it can operate for an extended time on a battery and requires very infrequent maintenance—just like BLE.

LoRa nodes are also inexpensive, allowing companies to create a low-cost backhaul network that bypasses fiber or cell service. Thus, they are able to avoid the high cost of building fiber to a remote site or the cost of a cell contract. These costs

can be expensive for the kind of connectivity needed with an IoT deployment.

LoRa is also highly scalable and highly interoperable, supporting up to a million nodes and compatible with both public and private networks for the data backhaul and bidirectional communications. And one of its best qualities is the ability to perform in environments with vibration, interference, extreme temperatures, etc. These conditions are quite common in industrial environments and remote locations where the elements can go to extremes.

Together, BLE and LoRa provide the combination of short-range, inter-device communications and long-haul backhaul over distance to allow the implementation of IoT networks in a much broader geographic area. This geographic freedom is particularly important for enterprise-level IoT, because so often these wireless networks of sensors and devices are located a great distance from urban areas (*see figure*).

With that said, some exciting applications await LoRa in metro areas: A few LoRa gateways can create an IoT network for a large urban area, connecting a large number of devices with their own low-power network that need not rely on traditional telecom infrastructure. Those applications include environmental monitoring, to city management, to utility-meter measurements among dozens of others.

Those non-far-flung applications are fascinating, but what makes LoRa+BLE so significant is how it turns nearly anyplace on the map into a realistic location for an IoT deployment. As an example of LoRa+BLE in action, take a basic temperature sensor, which is one of the most common types of devices in IoT deployments. It could measure the temperature of an exhaust outlet on a generator in a remote location, or measure changes in temperature of liquid oil in a holding tank, or measure air temperature in an environmentally sensitive wilderness area. Regardless of the location, it's still a temperature-sensor deployment at heart, which most engineers have done at least once—if not a thousand times.

But for the sake of this example, let's say that there isn't any telecom infrastructure anywhere close enough to be of practical use. The short-range network of sensors would look very familiar to many because it is a BLE-based network of wireless devices. However, with a LoRa+BLE module in those devices, and a LoRa gateway to provide the long-haul data transfer, that network of IoT devices can perform the task even with no Wi-Fi or cellular service in sight.

The LoRa gateway on-site would relay data packets to and from the cloud via a series of small nodes every 10 miles, each of which utilize the ultra-low-power LoRa to stay running for long periods on a small battery. That backhaul can extend as far as necessary until a connection is able to be

made to traditional telecom infrastructure. This means IoT networks can be 10 miles or hundreds of miles further away than previously possible, dramatically expanding where these networks can go.

Now when you spin a globe and put your finger down randomly on any far-flung corner of the earth, not only can you daydream about taking a vacation there, you can daydream about putting an IoT network in that spot as well. **mw**

### LOOKING AT THE LoRaWAN SPECIFICATION

**LoRaWAN TARGETS KEY** IoT requirements, such as secure bidirectional communication, mobility, and localization services. The LoRaWAN specification provides seamless interoperability among smart “things” without the need for complex local installations, thus giving back the freedom to the user, developer, and businesses, and enabling the rollout of IoT.

LoRaWAN network architecture is typically laid out in a star-of-stars topology. In this configuration, a gateway is a transparent bridge relaying messages between end devices and a central network server

in the backend. Gateways are connected to the network server via standard IP connections, while end devices use single-hop wireless communication to one or many gateways. All end-point communication is generally bidirectional. However, it also supports operations such as multicast, enabling software upgrades over the air or other mass-distribution messages to reduce the on-air communication time.

Communication between end devices and gateways is spread out on different frequency channels and data rates. The

selection of the data rate is a tradeoff between communication range and message duration. Due to spread-spectrum technology, communications with different data rates do not interfere with each other and create a set of “virtual” channels, increasing the capacity of the gateway. LoRaWAN data rates range from 0.3 to 50 kb/s. To maximize battery life of the end devices as well as overall network capacity, the LoRaWAN network server manages the data rate and RF output for each end device individually by means of an adaptive-data-rate (ADR) scheme. ■

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|              | Frequency Range | Gain    | Noise Figure | P1dB     | Psat     | OIP3     | Bias Supply |         |
|--------------|-----------------|---------|--------------|----------|----------|----------|-------------|---------|
| Model Number | GHz             | dB Typ. | dB Typ.      | dBm Typ. | dBm Typ. | dBm Typ. | V/mA        | Package |
| EMD1710      | 2.0 - 20        | 12.5    | 2.0          | +18.5    | +19.0    | +28.0    | 5/83        | QFN 4mm |
| EMD1715      | DC - 20         | 14.5    | 1.8          | +20.5    | +23.5    | +28.0    | 5/103       | QFN 4mm |
| EMD1725-D    | DC - 40         | 15.0    | 3.5          | +20.5    | +23.0    | +33.0    | 8/108       | DIE     |

- Features**
- +5 or +8 volt supply.
  - Low noise figure.
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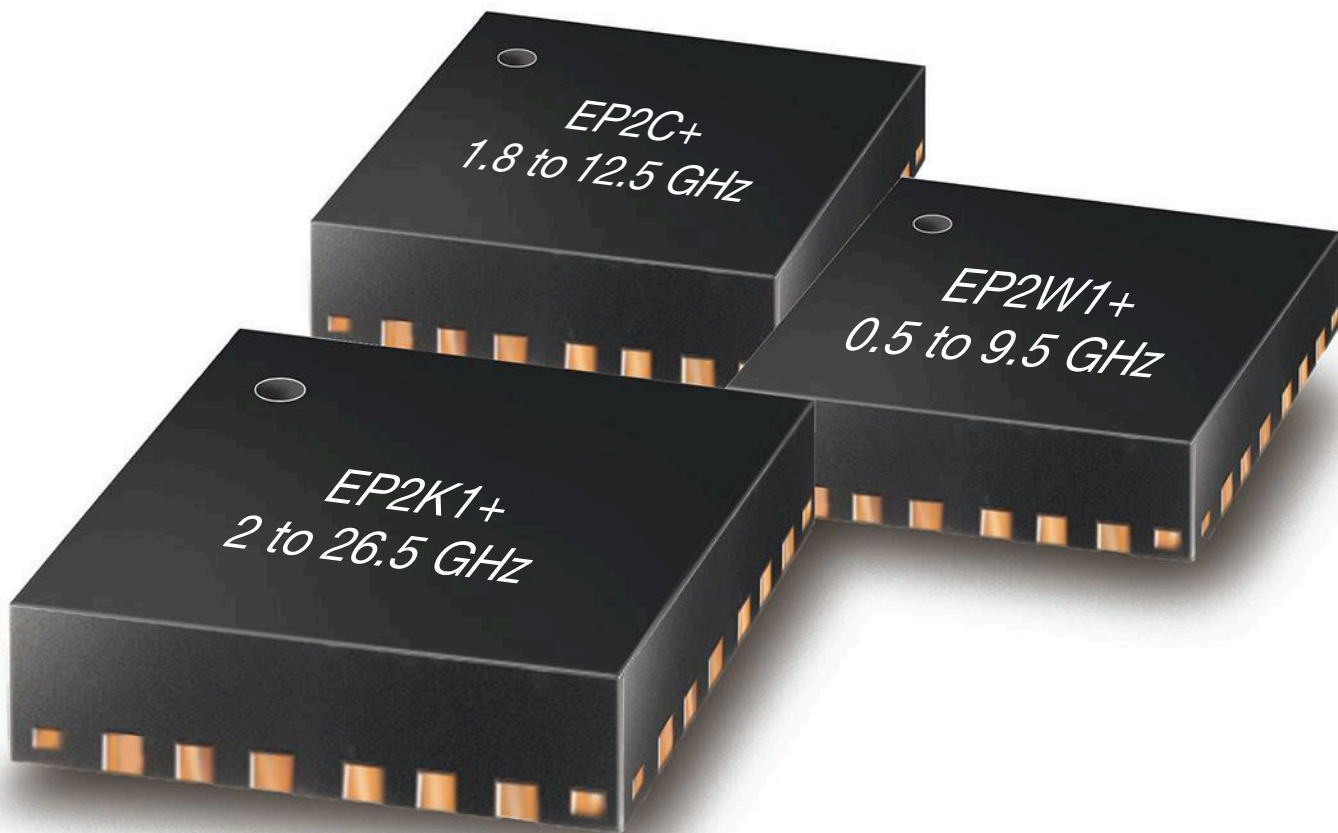
- Applications**
- General purpose
  - Commercial and industrial
  - Microwave radio & VSAT
  - Test instrumentation
  - Telecom & Fiber optics

**Product export classification**  
ECCN: EAR 99 (unless otherwise specified)  
HTS: 8542330000

Eclipse Microdevices EMD1710 and EMD1715 are ideal for applications that require a typical noise figure as low as 2.0 dB across the DC- 20 GHz band, while requiring only 83mA/103mA from a +5V supply. The EMD1725-D has a typical noise figure of 3.5dB to 40 GHz. The EMD1700 series are available in 4mm QFN packages and bare die (1725-D only).

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 EP2K-Series, 4x4x1mm

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# Pointing to Progress in Probe Stations

**Mechanical precision and repeatability enable RF/microwave probe stations to support on-wafer measurements through millimeter-wave frequencies.**

**WAFER PROBES AND** probe stations are marvels of mechanical engineering. They are capable of delicately maneuvering measurement probe contacts onto micron-sized circuit features with enough contact force to make meaningful measurements without causing damage to the circuits. As semiconductor wafers have grown in size, designers of wafer probe stations have responded with probe stations capable of handling larger wafers with precision. At higher frequencies, it is the precision needed for millimeter-wave S-parameter measurements. Modern probes and probe stations provide the placement precision for on-wafer measurements to 70 GHz and beyond.

Semiconductor wafer probing systems are available as manual, semi-automated, and fully automated systems. Working with test probes mounted in micro positioners, they can achieve the precision needed to place a probe tip onto a miniature test point, such as an IC's probe pads. With that contact made, microwave test equipment such as a vector network analyzer (VNA) can be used to characterize circuit or device electrical behavior for modeling and packaging purposes.

As ICs move towards higher frequencies and smaller wavelengths, device dimensions continue to shrink, requiring even greater probe placement precision. Semiconductors are typically designed with probe contact pads as part of the circuit, but getting to these pads with the tip of an electrical probe requires positioning precision in all three axes. This is accomplished by a combination of probe station components, including the main probe station to hold and position a circuit under test and micro positioners to hold and position test probes.

In the case of the CM300xi probe station (Fig. 1) from Cascade Microtech ([www.cascademicrotech.com](http://www.cascademicrotech.com)), computer intelligence guides the probe positioning accuracy. Using what the company calls "Contact Intelligence" technology, this probe station detects on-chip probe positions and includes the effects of operating temperature when controlling the placement of the probe tip. In this way, the automated probe station can achieve the most-accurate probe-to-pad alignment possible for a measurement, covering a wide range of semiconductor materials, wafer sizes, and devices.



**1. The CM300xi probe station features micro positioners under computer control to achieve submicron positioning resolution and accuracy when placing a test probe on a circuit. (Courtesy of Cascade Microtech)**

The CM300xi probe station is modular and scalable, allowing a user to equip the system with as much or as little capability as needed. The system can handle 200- and 300-mm wafers, with an x-y travel range of 301 × 501 mm (11.9 × 19.7 in.). Movement is controlled by micro stepper motors with moving stages traveling on precision ball bearings. Placement accuracy in the x and y directions is better than 2 µm in standard operating mode and better than 0.3 µm in precision mode, with positioning speed of 50 mm/s (2 in./s). The z-axis stage moves with just as much precision over a travel distance of 10.0 mm (0.39 in.) The positioning accuracy in the z-axis is better than 2 µm, with repeatability of better than 1 µm. The positioning resolution in all three axes is 0.2 µm.

In addition to the Contact Intelligence capabilities, the CM300xi probe station is guided by the company's VueTrack software for rapid and accurate alignment of probe tips to probe pads. In addition, the Velox probe station control software simplifies the programmable operation of the probe station and integration with test equipment for fast, reliable automated measurements without causing damage to wafers under test (or probe tips, for that matter). For those who prefer, an open, non-EMI-shielded version of the system is also available without the Contact Intelligence technology. The company also produces systems for performing wafer-level-reliability (WLR) testing. The Estrada system, for example, can perform high-volume reliability testing on 300-mm wafers.



## Plug, test, smile

When it comes to test and measurement, SUCOFLEX® 526V and SUCOFLEX® 526S assemblies guarantee the highest level of satisfaction. Thanks to their unique cable and connector design, they deliver best-in-class phase and amplitude stability with flexure, movement, temperature and tensile stress in combination with outstanding return and insertion loss up to 26.5 GHz.

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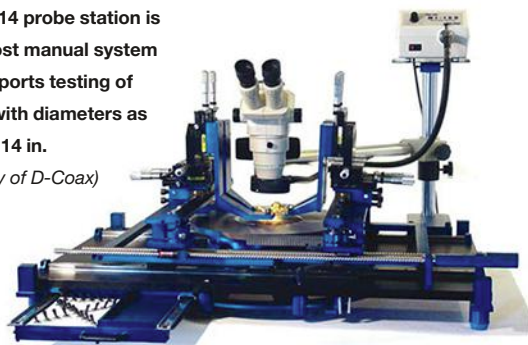
### EXPLORING OTHER OPTIONS

While Cascade Microtech may have done as much as any one company to define the current state of RF/microwave wafer probe technology, probe stations suited for RF/microwave probing are available from a number of other suppliers, including D-Coax ([www.d-coax.com](http://www.d-coax.com)), Lake Shore Cryotronics ([www.lakeshore.com](http://www.lakeshore.com)), MicroXact ([www.microxact.com](http://www.microxact.com)), and SIGNATONE ([www.signatone.com](http://www.signatone.com)).

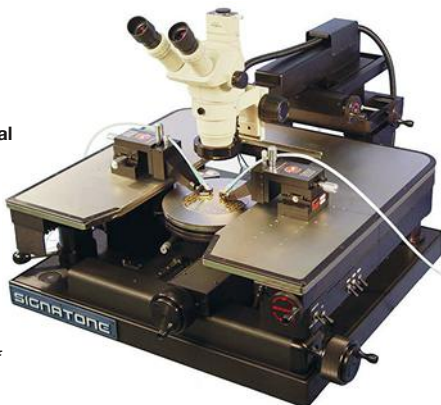
For example, D-Coax offers its D14 probe station (Fig. 2) for those on tight budgets. It is a versatile manual system with independent vacuum control to accommodate micro positioners for wafer diameters of 3, 6, 8, 10, 12, and 14 in. It incorporates 17 independently operated vacuum positions for calibration substrates and other devices and includes vibration-isolating feet in a relatively small footprint. In support of the probe station, the company provides RF/microwave probes, coaxial cable assemblies to 67 GHz for interconnections to test equipment such as VNAs and calibration substrates. It also recommends RF/microwave probes from GGB Industries ([www.ggb.com](http://www.ggb.com)).

**2. The D14 probe station is a low-cost manual system that supports testing of wafers with diameters as large as 14 in.**

(Courtesy of D-Coax)



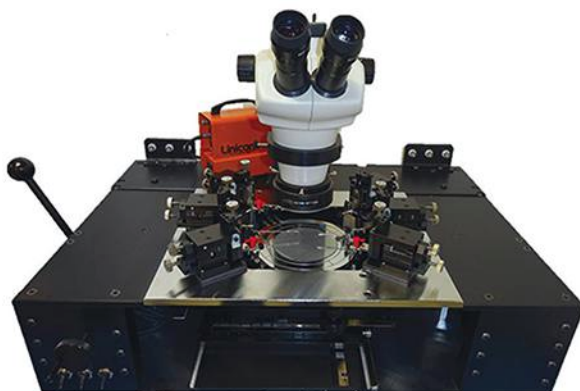
**3. The WL-210 RF/microwave probe station uses manual control of micro positioners to move a test probe to the desired location on a wafer or circuit.** (Courtesy of SIGNATONE)



In some cases, such as for R&D, automation may not be needed and a manual probe station may provide the capability required to probe a packaged or unpackaged device. The WL-210 RF/microwave probe station (Fig. 3) from SIGNATONE ([www.signatone.com](http://www.signatone.com)) is a member of the company's

WAVELINK family of RF/microwave wafer probe stations. The WL-210, which can handle wafers as large as 8 in., features a base formed of 2-in.-thick aircraft-grade aluminum for stability. The probe station is designed not to resonate and weighs about 200 lb. (91 kg).

It has three substrate sites for mounting various formats of calibration substrates and is capable of probing wafers, packaged devices, and even printed-circuit boards (PCBs). The x-y stage has a full travel range of 200 × 200 mm by means of carriage-and-rails bearings and a rotary control. The resolution of the x-y stage movement can be set coarse (5 mm/turn) or fine (0.5 mm/turn). It features a nonferrous chuck and stage and supports a variety of micro positioners, including with magnetic base, vacuum, and bolt-down configurations.



**4. Manual probe stations in the SPS-2000 series provide a range of motion of 100 × 100 μm or more with 5-μm positioning resolution.**

(Courtesy of MicroXact)

Similarly, the SPS-2000 probe station (Fig. 4) from MicroXact ([www.microxact.com](http://www.microxact.com)) is a fully manual station with x-y range of travel of 100 × 100 μm or more and 5 μm positioning resolution. Standard SPS-2000 probe stations are designed to handle wafers with diameters as large as 100 μm, although stations with larger capacities can be provided. Numerous options are available, including a vibration isolation table, three-axis micro positioners, and precision microscopes.

For RF/microwave probe-based measurements, precision is needed—not just to prevent damage to the circuit under test, but also to preserve a typically expensive test probe. Tight control over the z-axis motion can help prevent probe tip damage and provide repeatable electrical contacts for testing.

Although measurements with a test probe are normally associated with on-wafer circuits, the increasing use of millimeter-wave frequencies for automotive radar systems and 5G wireless networks will prompt the use of “wafer” probes for an increasing number of non-wafer circuits, including PCB modules for millimeter-wave applications. The speed and accuracy of RF/microwave probe stations will contribute a great deal to enabling the commercialization of millimeter-wave circuits. **mw**

# Low-Loss Cables Connect to 40 GHz

These rugged cables stand the test of multiple mating cycles in measurement systems requiring high durability with extremely low insertion and return losses through 40 GHz.



The KBL series of fixed-length coaxial cable assemblies, featuring rugged armor construction and stainless-steel 2.92-mm connectors, can handle dc to 40 GHz.

**COAXIAL CABLES ARE** those often-overlooked components in a high-frequency systems, usually only noticed when they fail due to overworked or over-torqued connectors or over-flexed conductors. One line of coaxial cables built to last is the KBL series from Mini-Circuits ([www.minicircuits.com](http://www.minicircuits.com)), with high-quality plated conductors, rugged armor jacket, and durable 2.92-mm connectors. The combination of low-loss cables and connectors results in a line of fixed-length cables with instrument-grade performance from dc to 40 GHz.

The KBL coaxial cable assemblies (*see figure*) are available in stock lengths of 1.5, 2, and 4 ft., as well as 1- and 2-m and custom lengths. The RoHS-compliant cables use a solid silver-plated, copper-clad-steel center conductor and round silver-plated, copper outer conductor. The cables achieve excellent insulation between the conductors with polytetrafluoroethylene (PTFE) dielectric, and are fortified by means of stainless-steel spiral armor with a stainless-steel braid. The cables feature a protective shield and strain relief for long life and are terminated at both ends with stainless-steel 2.92-mm connectors. A blue PVC outer jacket protects the cables.

The connectors are designed to handle a large number of mating cycles with minimal performance degradation, and mate with K, 3.5-mm, and SMA connectors. The design and assembly of the coaxial cable assemblies results in reliable long-term performance, especially in test-and-measurement applications where connectors are attached and removed repeatedly to a test port or a device under test (DUT).

The cable assemblies exhibit low insertion loss and return loss (VSWR), with loss increasing as a function of increasing frequency. For example, for the shortest cable assembly, the 1.5-ft.-long KBL-1.5FT-LOW+, insertion loss is typically 0.49 dB from dc to 6 GHz, 0.85

dB from 6 to 18 GHz, 1.10 dB from 18 to 26.5 GHz, and 1.41 dB from 26.5 to 40 GHz. Return loss is typically 25 dB from dc to 6 GHz, 20 dB from 6 to 18 GHz, 18 dB from 18 to 26.5 GHz, and 17 dB from 26.5 to 40 GHz.

For the somewhat longer 1-m (about 3.28 ft.) KBL-1M-LOW+ cable assembly, insertion loss is typically 1.06 dB from dc to 6 GHz, 1.87 dB from 6 to 18 GHz, 2.35 dB from 18 to 26.5 GHz, and 3.05 dB from 26.5 to 40 GHz. Return loss is typically 25 dB from dc to 6 GHz, 20 dB from 6 to 18 GHz, 19 dB from 18 to 26.5 GHz, and 17 dB from 26.5 to 40 GHz. The *table* provides a quick comparison of loss performance for the cables from dc to 40 GHz.

The KBL coaxial cable assemblies are designed for operating temperatures from -55 to +85°C. All of the cables are rated for power-handling capabilities of 53 W at 2 GHz, 17 W at 18 GHz, 15 W at 26.5 GHz, and 11 W at 40 GHz. With their rugged armored construction, low-loss plated conductor materials, and stainless-steel connectors, these are coaxial cable assemblies that won't be overlooked, especially because of their ability to deliver reliable electrical connections when needed through 40 GHz. **mw**

MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-003; (718) 934-4500, FAX: (718) 332-4661, [www.minicircuits.com](http://www.minicircuits.com).

| KBL CABLE ASSEMBLIES AT A GLANCE |         |                |                |                |                |
|----------------------------------|---------|----------------|----------------|----------------|----------------|
| Model                            | Length  | Insertion loss |                | Return loss    |                |
|                                  |         | DC-18 GHz (dB) | 18-40 GHz (dB) | DC-18 GHz (dB) | 18-40 GHz (dB) |
| KBL-1.5FT-LOW+                   | 1.5 ft. | 0.85           | 1.41           | 20             | 17             |
| KBL-2F-LOW+                      | 2.0 ft. | 1.05           | 1.74           | 20             | 17             |
| KBL-4F-LOW+                      | 4.0 ft. | 2.13           | 3.41           | 17             | 14             |
| KBL-1M-LOW+                      | 1 m     | 1.87           | 3.05           | 20             | 17             |
| KBL-2M-LOW+                      | 2 m     | 3.41           | 5.46           | 20             | 17             |

# goTenna Sets Sights on Off-Grid Tactical Communications

With its focus on enabling off-grid communications, this company's latest product turns a smartphone into a mission-critical communications tool—without needing any centralized infrastructure.

**TODAY, CELLULAR PHONES** obviously represent a major part of life for many people. However, what good are those phones when service is unavailable? That question was asked by siblings Jorge and Daniela Perdomo in the wake of Hurricane Sandy. That storm sparked a belief in them that cell phones were practically useless when actually needed the most. Thus, goTenna ([www.gotenna.com](http://www.gotenna.com)) was founded by Jorge (VP) and Daniela (CEO) with a goal of enabling off-grid communications. The company is located in Brooklyn, N.Y.

Essentially, the company wanted to enable people to communicate with a phone without needing cellular, internet, or satellite service. Hence, goTenna's first product, also named goTenna, was launched in 2015. The goTenna device can be wirelessly paired to a smartphone via Bluetooth low energy (BLE). The company's simple messaging app then allows that smartphone to exchange messages and share GPS locations with other goTenna users within range—all without requiring service. Thus, communication is possible in all types of situations, such as hiking in remote areas, traveling, attending music or sporting events, and during emergencies, according to goTenna.

## ENTER THE GOTENNA PRO

Following the introduction of the goTenna device, the company saw demand for a more enhanced product. That paved the way for the new goTenna Pro, a mesh networking tactical radio that can work with any smartphone (*Fig. 1*). While the first goTenna device is a consumer product, the goTenna Pro is intended for applications like defense, public safety, wildland firefighting, and many others.

The goTenna Pro, which is about the size of a candy bar, takes advantage of mesh networking technology to further enhance off-grid communications. Moreover, it can achieve more than 60 hours of battery life from a single 3.5Wh battery

1. Roughly the size of a candy bar, this professional-grade radio utilizes mesh networking technology.

2. The smartphone app allows for text messaging and live interactive mapping.



and can be fully recharged within six hours.

The goTenna Pro operates over frequency ranges of 142 to 175 MHz and 445 to 480 MHz. It can transmit 5 W of output power. In addition, the goTenna Pro's SMA connector allows it to be integrated with off-the-shelf antennas or systems.

Like the goTenna, the goTenna Pro operates with a smartphone app to allow for messaging and location sharing (*Fig. 2*). "We're very proud of the app being simple," explained Jorge Perdomo. "We didn't want to create an app that had all these elements that people had to learn how to use." In addition, the software development kit (SDK) allows for the building of other applications.

The goTenna Pro is available for \$499. [mww](http://mww)



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# Q&A: Kris Myny

## Principal Member of Technical Staff at imec

**In this interview, Kris Myny discusses how imec technology, such as metal-oxide thin-film transistors, has the potential to impact everyday products and services.**

**First, can you tell us a little about imec?**

Founded in 1984 in Leuven, Belgium, imec is an R&D and innovation hub in nanoelectronics and digital technologies. The combination of advanced microchip technologies and state-of-the-art software expertise is what makes imec unique. The evolution in microchip technology toward more powerful and smaller chips allows us to make every object intelligent and bring tons of data to our fingertips.

imec pioneers compact, high-throughput, and power-efficient design solutions for next-generation wireless communication. Our portfolio includes millimeter-wave phased-array transceivers, record-breaking analog-to-digital converter

(ADCs), reconfigurable low-noise frequency synthesizers, tunable duplexers, and more. Our solutions cover the entire spectrum of wireless communication ranging from LTE to 5G.

In addition to our headquarters in Belgium, imec has research facilities in the Netherlands, Taiwan, China, and India, as well as offices in Japan and the U.S. In 2016, imec opened a new facility in Florida—a design center facilitating collaboration between imec's headquarters in Leuven and U.S.-

based semiconductor and system companies, universities, and research institutes.

The initial focus of the new facility will be R&D of high-speed electronics and photonics solutions. It will start with IC design research for a broad set of semiconductor-based solutions such as terahertz (THz) and LIDAR (light detection and ranging) sensors and imagers.

**Recently, imec introduced its near-field-communications (NFC) tag that is manufactured with thin-film transistor technology. How will this impact NFC-based products?**

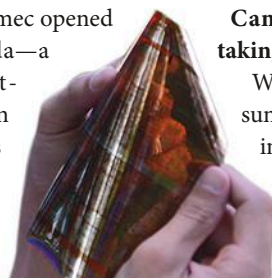
Metal-oxide thin-film transistors represent a widespread transistor technology mainly used today as switches in active matrix displays, like AM-OLED and AM-LCD. In addition, at imec, we investigate the applicability of metal-oxide transistor technology in flexible integrated-circuit applications, like low-cost RFID/NFC tags and microprocessors on foil.

The key challenge for metal-oxides is to achieve sufficient performance required for those applications, given the  $\mu\text{m}$  channel lengths and a charge carrier mobility of around  $10\text{ cm}^2/\text{Vs}$ . Our recent demonstration of the world's first flexible metal-oxide NFC tag, read out by a commercial smartphone, is therefore a big milestone for the field, showcasing for the first time metal-oxide thin-film circuits that comply with ISO standards.

This low-cost, ultra-thin, flexible NFC technology enables a seamless integration into everyday objects for Internet of Things (IoT) applications. An object can connect to the cloud using the smartphone as a hub and NFC as communication medium. It can be simple identification of the object, like NFC-based playing cards interacting with smartphones and tablets (referring to our developments together with our partner Cartamundi). Moreover, the object can contain sensor readout in the future, paving the way to revolutionize retail (like cold-chain monitoring, drone delivery, etc.) and wearable health patches.

**Can you talk about some of the developments taking place at imec for low-power IoT radios?**

We cover a wide range of IoT applications, from consumer health and well-being to smart homes/ buildings/cities and industrial applications. We empower new applications by drastically reducing power consumption for wireless connectivity, enabling operation from small batteries or energy harvesters and smaller device form factors. **ttw**



## Four-Way 0-deg. Power Splitter/Combiner Channels 2 to 18 GHz

Mini-Circuits' model ZN4PD-02183+ is a DC-pass, four-way power splitter/combiner with low loss from 2 to 18 GHz. It features typical full band insertion loss of only 1 dB above the theoretical 6-dB splitting loss. The typical isolation between ports is 20 dB, which it maintains across the full frequency range. The typical full band phase unbalance is 3.5 deg. and the typical full band amplitude unbalance is 0.3 dB. The RoHS-compliant, 50- $\Omega$  power splitter/combiner exhibits typical VSWR of 1.45:1 or better at all ports. It is supplied in a compact housing measuring 4.00 x 2.50 x 0.38 in. (63.50 x 101.60 x 9.65 mm) with SMA female connectors and designed for operating temperatures from -55 to +100°C. It is capable of handling 30 W input power as a splitter.



## MMIC SPDT Switch and Driver Control 100 MHz to 6 GHz

Mini-Circuits' model HSWA2-63DR+ is an absorptive single-pole, double-throw (SPDT) RF switch with internal driver for applications from 100 MHz to 6 GHz. Housed in a tiny 4 x 4 mm, 20-lead MCLP package, it is usable down to 1 kHz. The typical isolation between ports is 69 dB at 1 GHz. With typical input 1-dB compression of +33 dBm, the switch features a high input third-order intercept point (IIP3) of +65 dBm. It provides high-speed switching, with typical switching time of only 300 ns from 50% control signal to 90% or 10% RF signal level. The typical insertion loss ranges from 0.95 dB at 100 MHz to 1.60 dB at 6 GHz. The RoHS-compliant switch draws 120 mA typical current from a supply of +2.7 to +5.5 V dc.



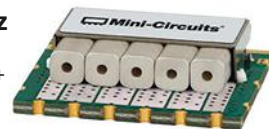
## 75- $\Omega$ Directional Coupler Spans 5 to 1250 MHz

Mini-Circuits' model RDC-10-122-75X+ is a 75- $\Omega$ , surface-mount directional coupler with 10-dB coupling from 5 to 1250 MHz. It achieves 20-dB typical full band directivity with 20-dB typical full band return loss and handles as much as 1 W (+30 dBm) input power. The coupler has low mainline loss of typically 1.1 dB to 1000 MHz and 1.3 dB to 1250 MHz. The typical coupling flatness is  $\pm 0.01$  dB. The broadband RoHS-compliant coupler supports requirements for cable-television (CATV) and DOCSIS® 3.1 systems. It handles operating temperatures from -40 to +85°C and is supplied in a core-and-wire configuration measuring 0.25 x 0.280 x 0.140 in. (6.35 x 7.11 x 3.56 mm) with Top Hat® feature for ease of handling and mounting.



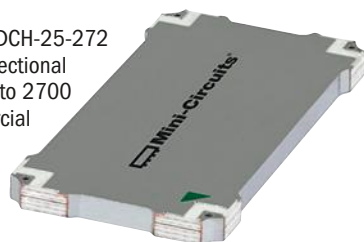
## Surface-Mount Filter Passes 1500 to 1760 MHz

Mini-Circuits' model CBP-1630F+ is a 50- $\Omega$ , surface-mount bandpass filter with passband of 1500 to 1760 MHz. Based on high-Q coaxial-ceramic-resonator construction, it has low passband insertion loss of typically 1 dB from 1500 to 1760 MHz and low passband VSWR of typically 1.50:1 from 1500 to 1760 MHz. The lower stopband rejection is typically 30 dB from DC to 1320 MHz while the upper stopband rejection is typically 30 dB from 1960 to 2600 MHz. Using a six-pole configuration for high selectivity, the compact bandpass filter is suitable for L-band applications in aviation, maritime, radio astronomy, and mobile-satellite systems. It handles input power levels to 1 W (+30 dBm) and operating temperatures from -40 to +85°C and is supplied in a shielded multipin package measuring 1.050 x 0.875 x 0.239 in. (26.67 x 22.23 x 3.18 mm).



## DC-Pass Bidirectional Coupler Handles 150 W to 2700 MHz

Mini-Circuits' model BDCH-25-272 is a high-power bidirectional coupler for use from 700 to 2700 MHz. Suitable for commercial and military applications, the 50- $\Omega$ , DC-pass coupler handles power levels to 150 W with low insertion loss of typically 0.2 dB. It provides typical full band return loss of 29 dB at all ports with typical directivity of 18 dB or better across the full frequency range. The typical coupling is 26.4 dB with  $\pm 1.2$  dB coupling flatness across the full frequency range. The bidirectional coupler measures just 0.5 x 1.0 x 0.051 in. and is supplied in an open printed-circuit laminate format with wrap-around terminations for good solderability. It is designed for operating temperatures from -55 to +105°C.



## LTCC Highpass Filter Screens 14.3 to 18.5 GHz

Mini-Circuits' model HFCN-1322+ is a low-temperature-cofired-ceramic (LTCC) highpass filter with passband of 14.3 to 18.5 GHz. The passband insertion loss is typically 1.75 dB or better, with typical VSWR of 1.70:1. The stopband rejection is typically 28 dB from DC to 11.7 GHz, with 3-dB loss at a cutoff frequency of 13.3 GHz. The rugged hermetically sealed filter is a good fit for electronic-warfare (EW) exciters and receivers; it measures just 0.12 x 0.06 x 0.04 in. but handles input power typically as high as 7 W. The temperature-stable filter has an operating temperature range of -55 to +100°C. It features wrap-around terminations for excellent solderability.



## New Products

### High-Power Amplifier Delivers 100 W to 6 GHz

**THE HPA-100W-63+** is a coaxial high-power solid-state amplifier capable of 100 W output power from 2,500 to 6,000 MHz. Suitable for laboratory test applications, such as boosting the power level of a commercial signal generator when performing antenna and EMC measurements or reliability tests on components, the rugged power amplifier provides 58-dB typical gain with 93-dB typical reverse isolation. The gain flatness is typically  $\pm 2$  dB across the frequency range. Supplied in a 3U rack-mount enclosure with Type N connectors, the high-power amplifier operates from AC line power from 85 to 264 V ac and is usable from 0 to  $+50^{\circ}\text{C}$ . It incorporates a fan-driven front-to-back cooling system and numerous safety features, including built-in over-temperature protection and immunity to open and short load conditions at saturated output power for high reliability. It bears the CE mark as a sign of EMC compliance for European markets.

**MINI-CIRCUITS**, P.O. Box 350166, Brooklyn, NY 11235-003; (718) 934-4500, [www.minicircuits.com](http://www.minicircuits.com)



### Real-Time Analyzer Captures 9 kHz to 20 GHz

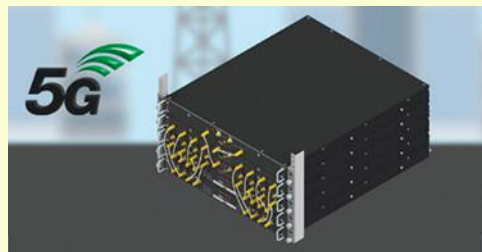
**THE SPECTRAN HF-80200 V5** real-time spectrum analyzer (RSA) can scan a total bandwidth of 9 kHz to 20 GHz in 20 ms to capture even short-duration signals. Versions of the analyzer are available with high-end frequencies of 6 through 20 GHz. The displayed average noise level (DANL) is  $-170$  dBm. The 1U-high instrument is suitable for rack mounting in fixed or mobile applications, including in satellite broadcast vehicles. It can be remote controlled via USB or LAN/Ethernet connection to a computer.

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### GaAs MMIC Power Amp Delivers +36 dBm to 20 GHz

**THE HMC-C582** is a GaAs MMIC pHEMT power amplifier developed by Analog Devices and available from stocking distributor Richardson RFPD. The amplifier runs on a single  $+15\text{-V}$  dc supply. It provides 24-dB gain and as much as  $+36$  dBm output power from 0.01 to 20 GHz. The gain is flat within  $\pm 1.5$  dB from 2 to 20 GHz. Inputs and outputs are DC blocked and internally impedance matched to  $50\ \Omega$ . A suitable candidate for radar, EW, fiber-optic, and test systems, the amplifier is supplied in a miniature hermetic module measuring  $1.75 \times 1.62 \times 0.525$  in. with SMA connectors.

**RICHARDSON RFPD**, 1950 S. Batavia Ave., Ste. 100, Geneva, IL 60134; (630) 262-6867, [www.richardsonrfpd.com](http://www.richardsonrfpd.com)



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**THE MILLIMETRE-WAVE 5G** Test System has been developed for characterizing the performance of high-frequency components for 5G applications. It extends the capabilities of the company's existing 4G modular test system to 28 GHz and beyond and is capable of emulating uplink or downlink communications channels in current 4G or anticipated future 5G wireless networks. The test system is comprised of five separate 1U rack-mount units that can be scaled for required channel capacities and frequency bands. The modules include two

radio modules, an output module capable of  $+10$  dBm signal power from 400 MHz to 6 GHz, a  $2 \times 8:1$  combiner module, and a 28-GHz frequency converter module with better than 1-GHz output bandwidth. As many as eight 100-MHz carriers can be aggregated into a single 800-MHz channel. Modules can also be supplied for 39 and 60 GHz bands and as high as 78 GHz.

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